Chapter 4

Properties Of Pure Substances

Objectives

- **Introduce the concept of a pure substance.**

- **Discuss the physics of phase-change processes.**

- **Illustrate the *P-v*, *T-v*, and *P-T* property diagrams and *P-v-T* surfaces of pure substances.**

- **Demonstrate the procedures for determining thermodynamic properties of pure substances from tables of property data.**

Objectives

- **Describe the hypothetical substance "ideal gas" and the ideal-gas equation of state.**

- **Apply the ideal-gas equation of state in the solution of typical problems.**

- **Introduce the compressibility factor, which accounts for the deviation of real gases from ideal-gas behavior.**

Ideal Gas Law vs Real Gas Law

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	Ideal Gas Law	**Real Gas Law**
DEFINITION	Ideal gas law is an equation which states the behaviour of an ideal gas	Real gas law is derived from the ideal gas law in order to fit the behaviour of real gases
THEORY	Describes the behaviour of a theoretical gas	Describes the behavior of actually occurring gases in the universe
EQUATION	$PV = nRT$	$(P + a\{n^2/V^2\})(V_m - b) = nRT$
SPECIFICATIONS	Has no specific components added because this equation is for an ideal gas	Has added a pressure component and a volume component to the ideal gas equation

PURE SUBSTANCE

Pure substance: A substance that has a fixed chemical composition throughout.

Air is a mixture of several gases, but it is considered to be a pure substance (because it has a uniform chemical Composition).
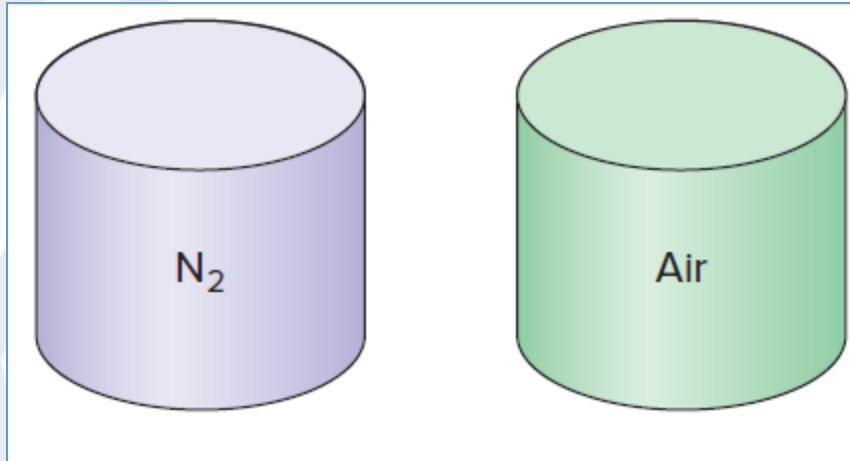

FIGURE 4-1

Nitrogen and gaseous air are pure substance
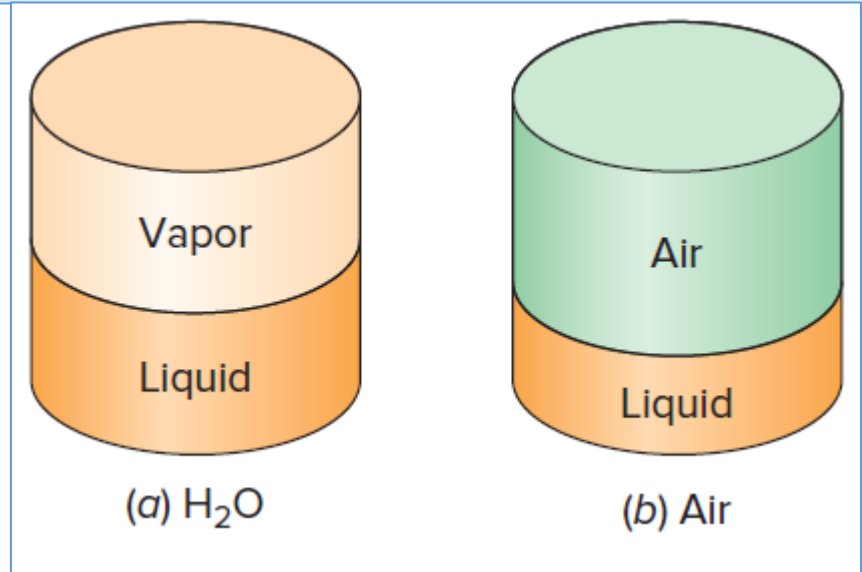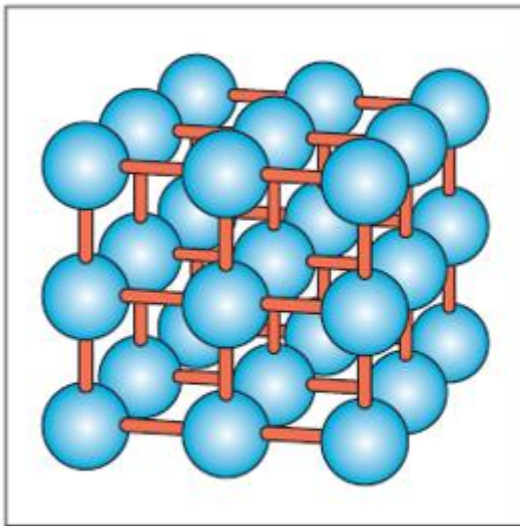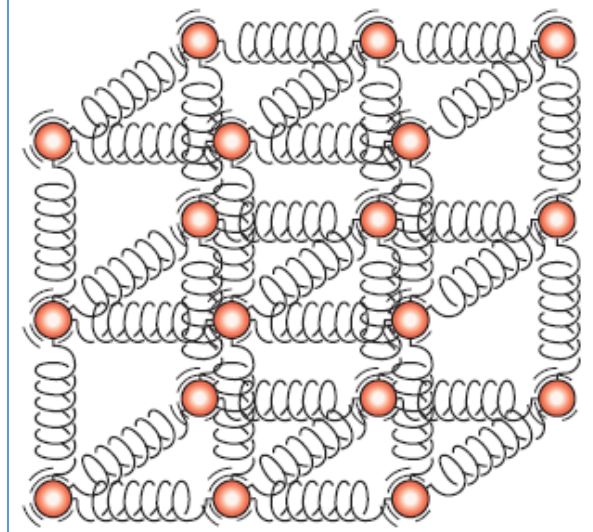

(a) H_2O (b) Air

FIGURE 4-2

A mixture of liquid and gaseous water is pure substance, but a mixture of liquid and gaseous air is not

4-2 PHASES OF A PURE SUBSTANCE

The molecules in a solid are kept at their positions by the large springlike inter-molecular forces.
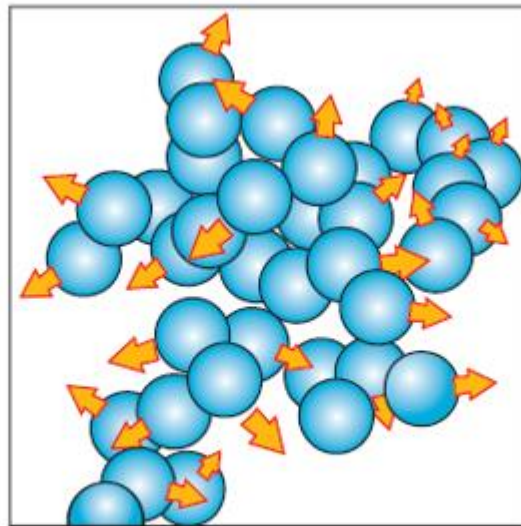
FIGUGE 4-4
The arrangement of atom in different phases:*(a)* molecules are at relatively fixed positions in a solid,*(b)* groups of molecules moves about other in the liquid phase, and *(c)* molecules move about at random in the gas phase.

Phase-change Processes Of Pure Substances

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Compressed liquid (subcooled liquid): A substance that it is *not about to vaporize*

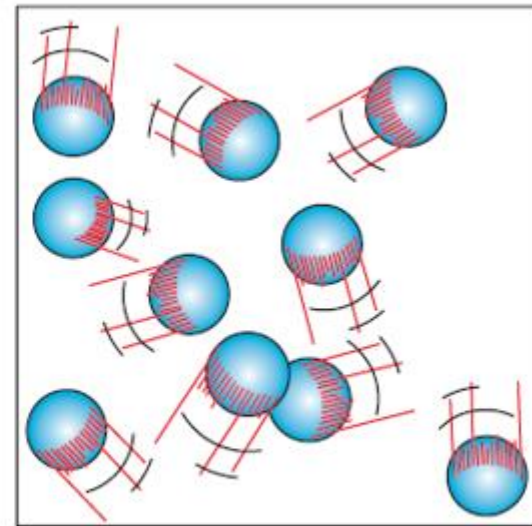**Saturated liquid:** A liquid that is *about to vaporize*

State 1

$P = 1$ atm
$T = 20°C$

Heat

State 2

$P = 1$ atm
$T = 100°C$

Heat
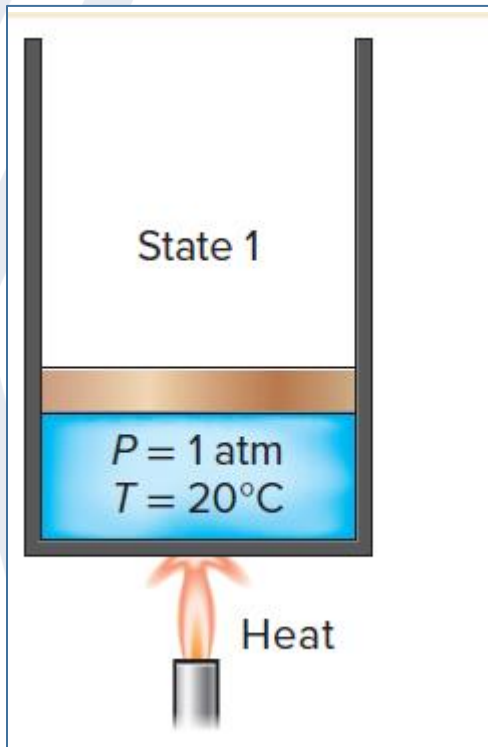
FIGURE 4-5
At 1 atm and $20°C$, water exists in the liquid phase (*compressed liquid*).
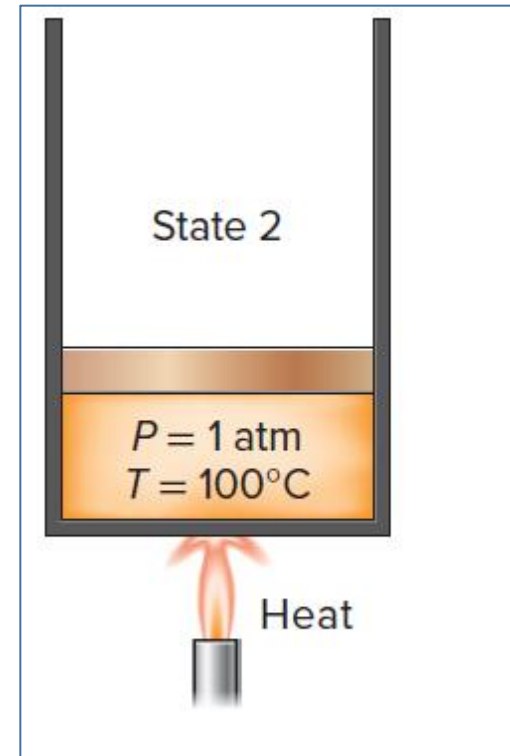
FIGURE 4-6
At 1 atm pressure and $100°C$, water exists in the liquid that is ready to vaporize (*saturated liquid*).

- **Saturated vapor**: A vapor **that is** *about to condense.*
- **Saturated liquid–vapor mixture**: **The state at which the** *liquid and vapor phases coexist* **in equilibrium.**
- **Superheated vapor**: **A vapor that is** *not about to condense* **(i.e., not a saturated vapor).**

State 3

Saturated vapor

$P = 1$ atm
$T = 100°C$

Saturated liquid

Heat

State 4

$P = 1$ atm
$T = 100°C$

Heat

State 5

$P = 1$ atm
$T = 300°C$
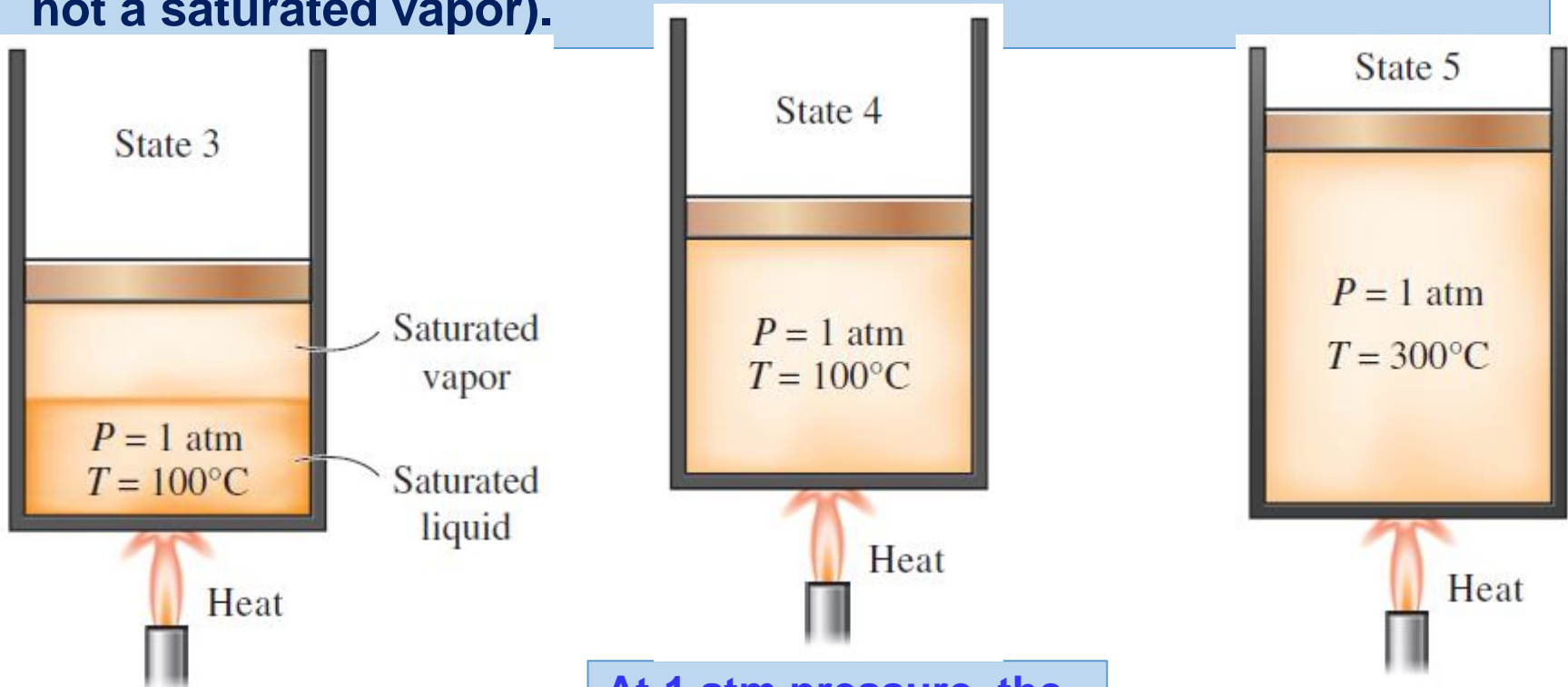
Heat

As more heat is transferred, part of the saturated liquid vaporizes (*saturated liquid–vapor mixture*).

At 1 atm pressure, the temperature remains constant at 100°C until the last drop of liquid is vaporized (*saturated vapor*).

As more heat is transferred, the temperature of the vapor starts to rise (*superheated vapor*).

If the entire process between state 1 and 5 is reversed by cooling the water while maintaining the pressure at the same value, **the water will go back to state 1,** retracing the same path, and in so doing, the amount of heat released will exactly match the amount of heat added during the heating process.
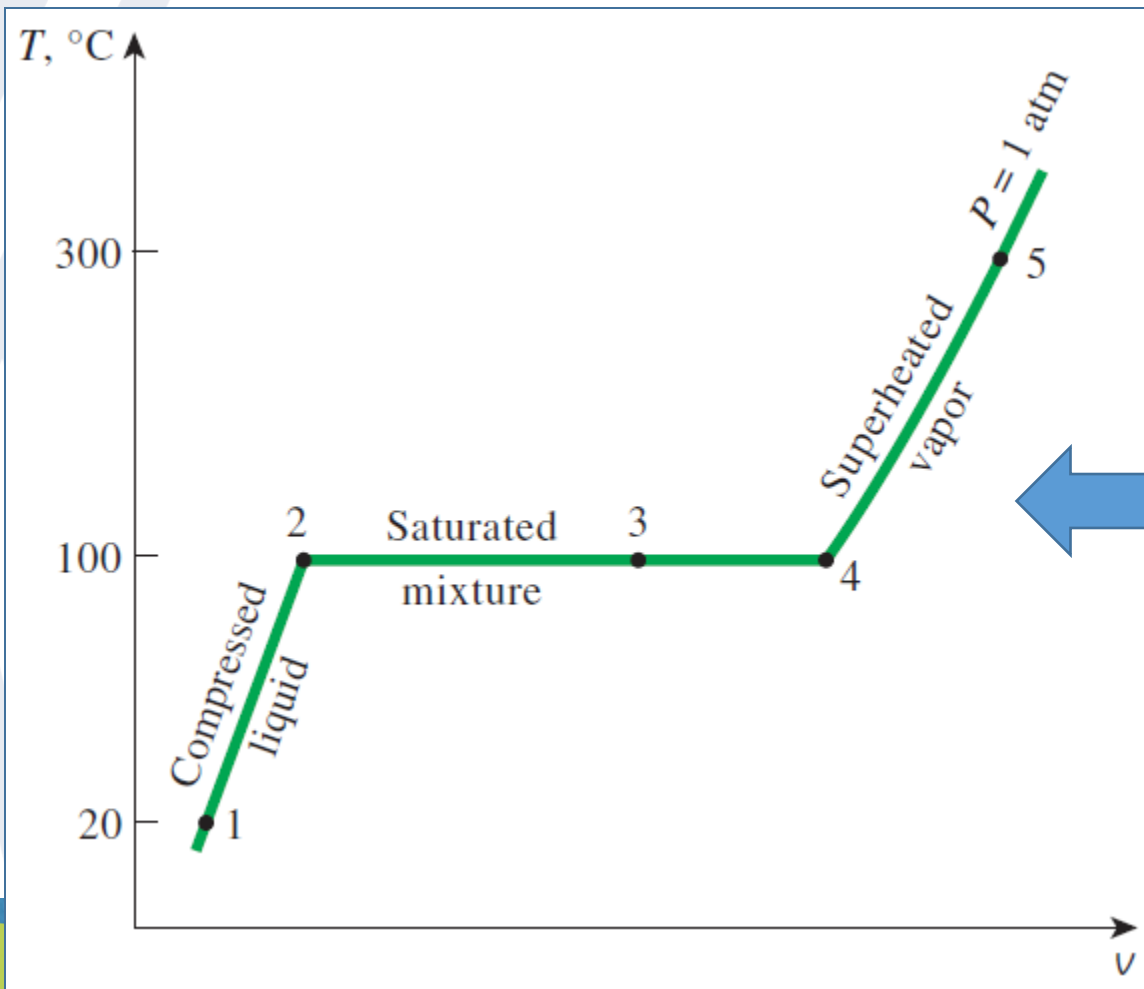
T-v diagram for the heating process of water at constant pressure.

Saturation Temperature and Saturation Pressure

The temperature at which water starts boiling depends on the pressure; therefore, if the pressure is fixed, so is the boiling temperature.

Water boils at $100°C$ at 1 atm pressure.

Saturation temperature T_{sat}: The temperature at which a pure substance changes phase at a given pressure.

Saturation pressure P_{sat}: The pressure at which a pure substance changes phase at a given temperature.

The liquid–vapor saturation curve of a pure substance (numerical values are for water).
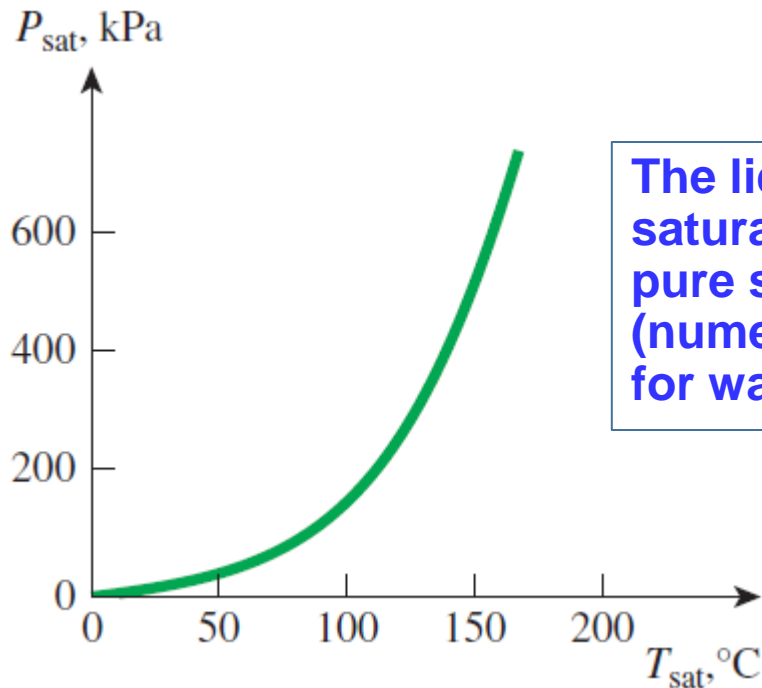
TABLE 4-1

Saturation (or vapor) pressure of water at various temperatures

Temperature T,°C	Saturation Pressure P_{sat}, kPa
-10	0.260
-5	0.403
0	0.611
5	0.872
10	1.23
15	1.71
20	2.34
25	3.17
30	4.25
40	7.38
50	12.35
100	101.3 (1 atm)
150	475.8
200	1554
250	3973
300	8581

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- **Latent heat: The amount of energy absorbed or released during a phase-change process.**

- **Latent heat of fusion: The amount of energy absorbed during melting. It is equivalent to the amount of energy released during freezing.**

- **Latent heat of vaporization: The amount of energy absorbed during vaporization, and it is equivalent to the energy released during condensation.**

TABLE 4-2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000	79.50	93.3
5,000	54.05	83.3
10,000	26.50	66.3
20,000	5.53	34.7

- **The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs.**

- **At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg.**

- **The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation.**

TABLE 4-2

Variation of the standard atmospheric pressure and the boiling (saturation) temperature of water with altitude

Elevation, m	Atmospheric pressure, kPa	Boiling temperature, °C
0	101.33	100.0
1,000	89.55	96.5
2,000	79.50	93.3
5,000	54.05	83.3
10,000	26.50	66.3
20,000	5.53	34.7

The variations of properties during phase-change processes are best studied and understood with the help of property diagrams such as the *T-v*, *P-v*, and *P-T* diagrams for pure substances.
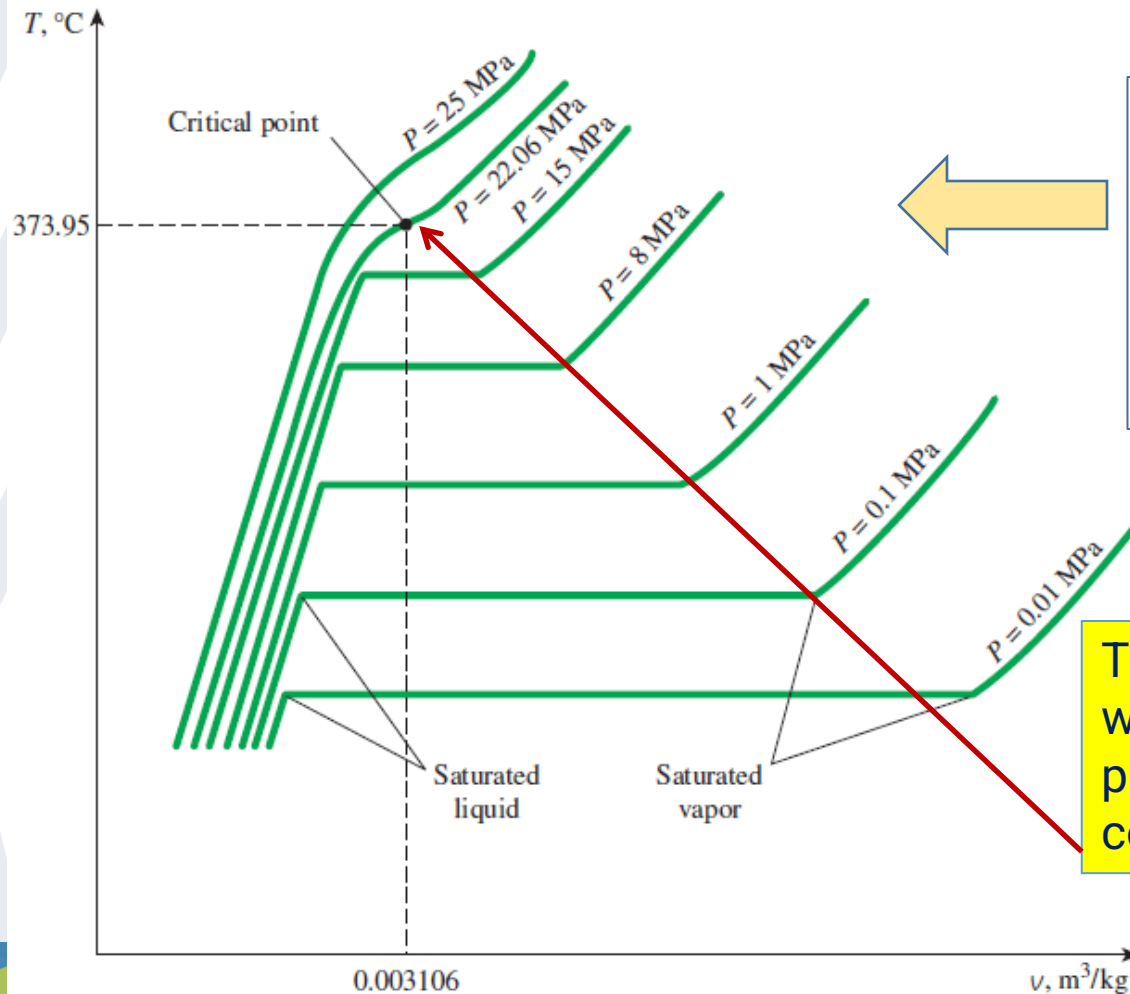
T-v diagram of constant-pressure phase-change processes of a pure substance at various pressures (numerical values are for water).

The temperature and pressure at which the solid, liquid, and vapor phases of a pure substance can coexist in equilibrium.

- **saturated liquid line**
- **saturated vapor line**
- **compressed liquid region**
- **superheated vapor region**
- **saturated liquid–vapor mixture region (wet region)**
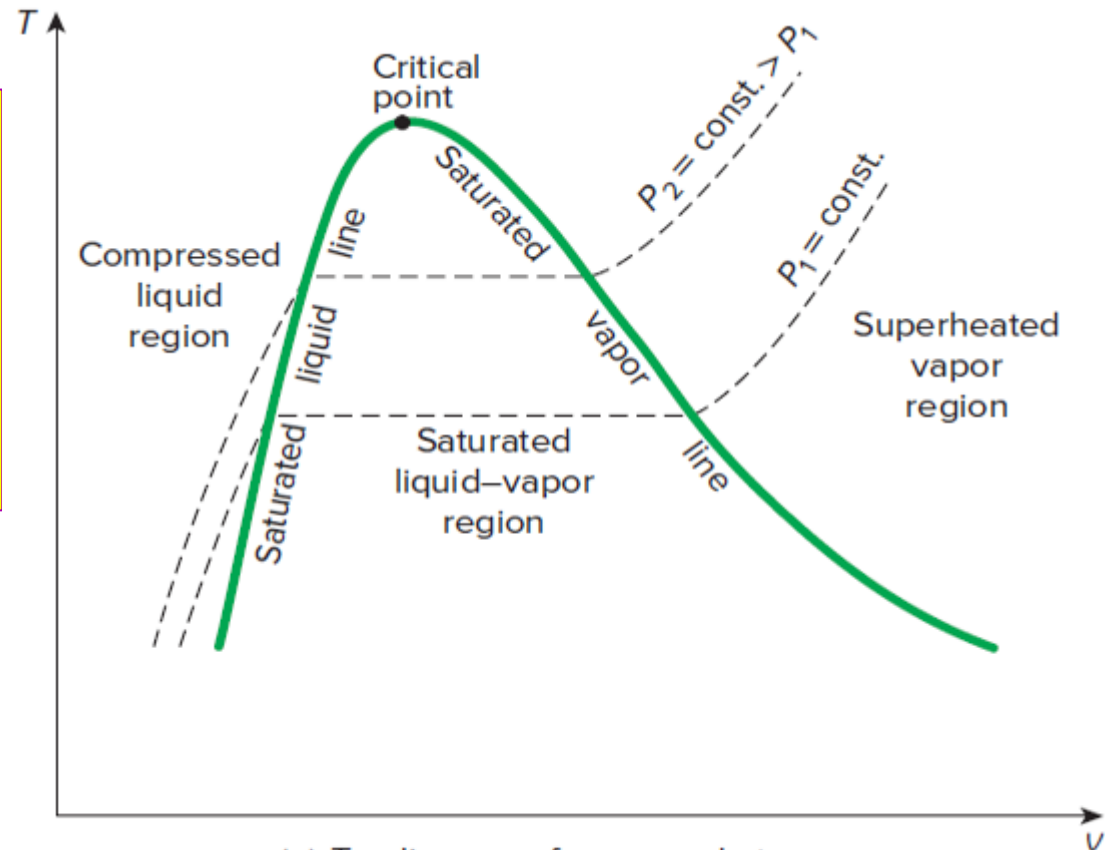
(a) T-v diagram of a pure substance

FIGURE 4-17
Property diagrams of a pure substance.
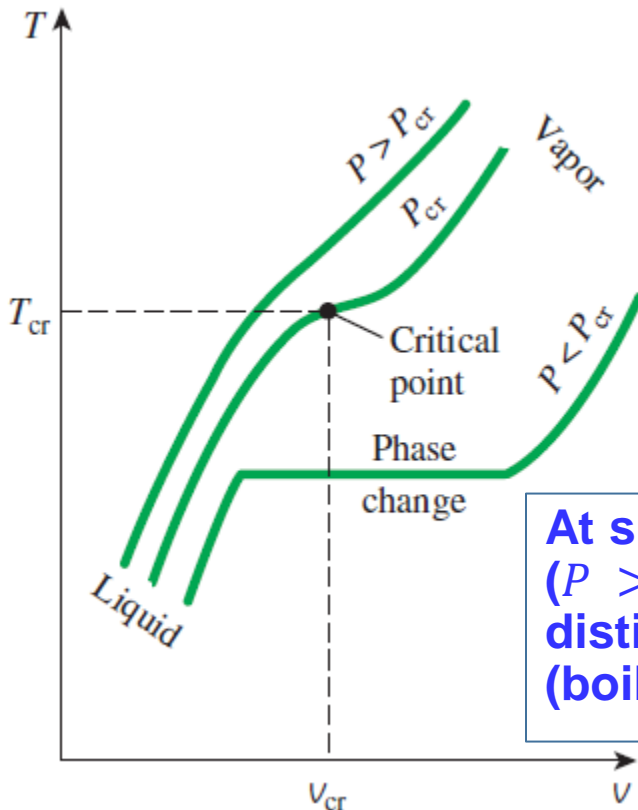
At supercritical pressures ($P > P_{cr}$), there is no distinct phase-change (boiling) process.

Critical point: The point at which the saturated liquid and saturated vapor states are identical.

4-4 Property Diagrams For Phase-change Processes-2
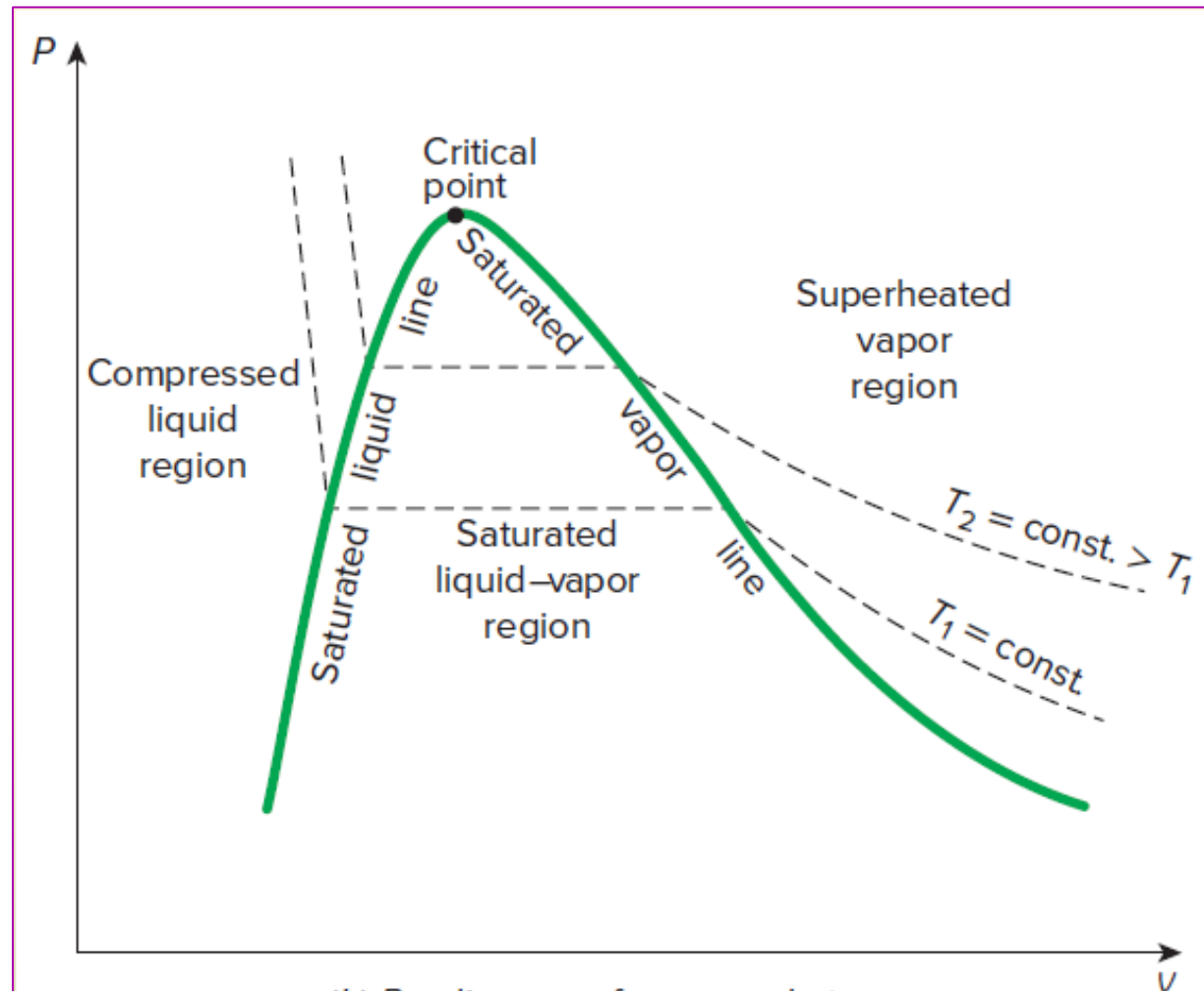
(b) P-v diagram of a pure substance

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For water,
T_{tp} **= 0.01°C**
P_{tp} **= 0.6117 kPa**

Extending The Diagrams To Include The Solid Phase

At triple-point pressure and temperature, a substance exists in three phases in equilibrium.

Vapor

Liquid

Solid
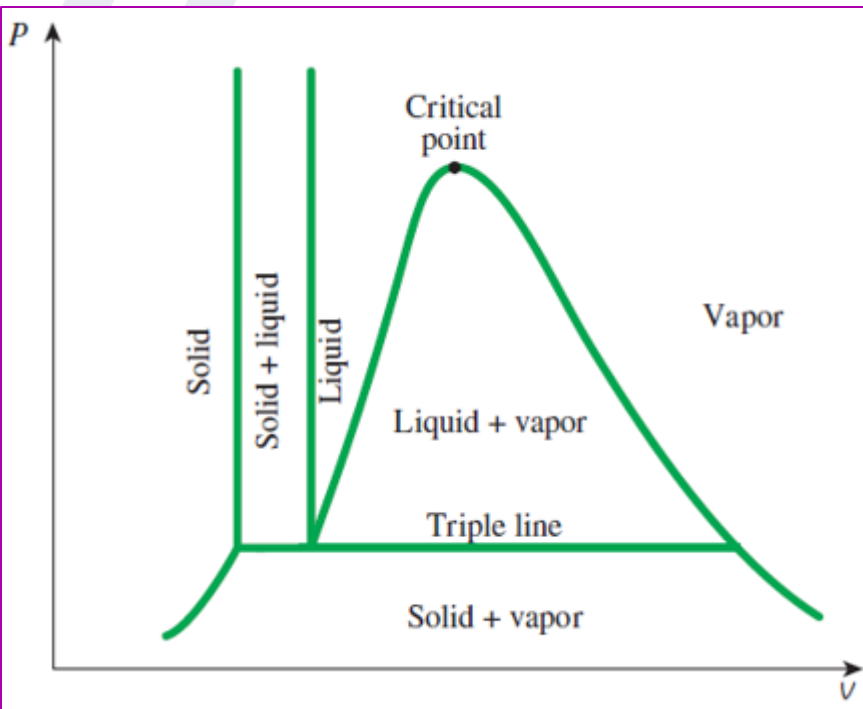
Fig. 4. 19. (a) P-v diagram of a substance that contracts on freezing
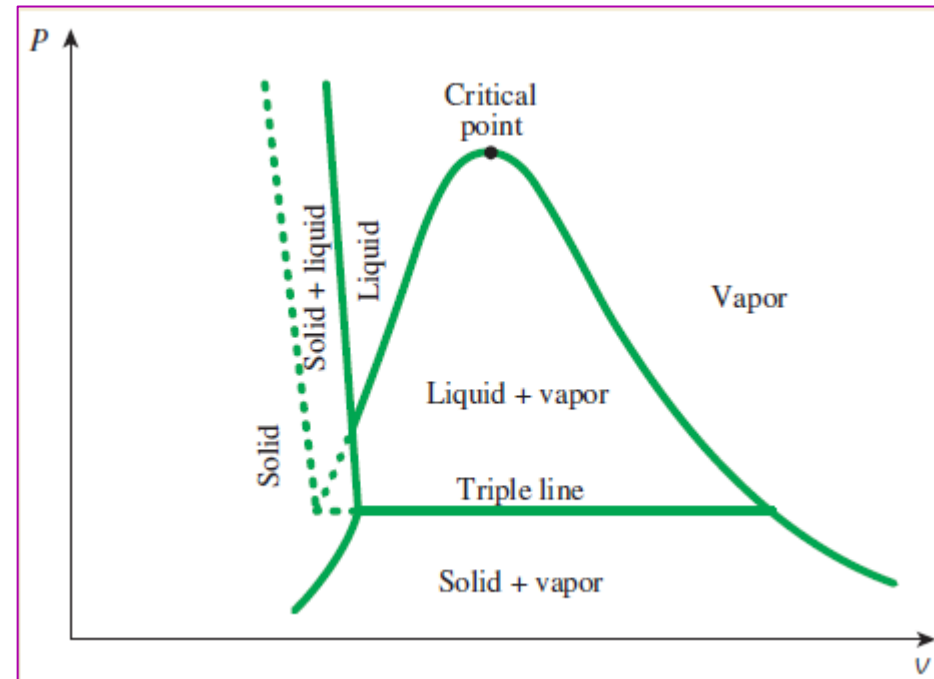
(b) P-v diagram of a substance that expands on freezing (such as water)

Triple and Critical point of a substance

- In thermodynamics, the **triple point** of a substance is the temperature and pressure at which the three phases (gas, liquid, and solid) of that substance coexist in thermodynamic equilibrium.

- It is that temperature and pressure at which the sublimation, fusion, and vaporisation curves meet.

- For example, the triple point of mercury occurs at a temperature of −38.8 °C (−37.8 °F) and a pressure of 0.165 mPa.
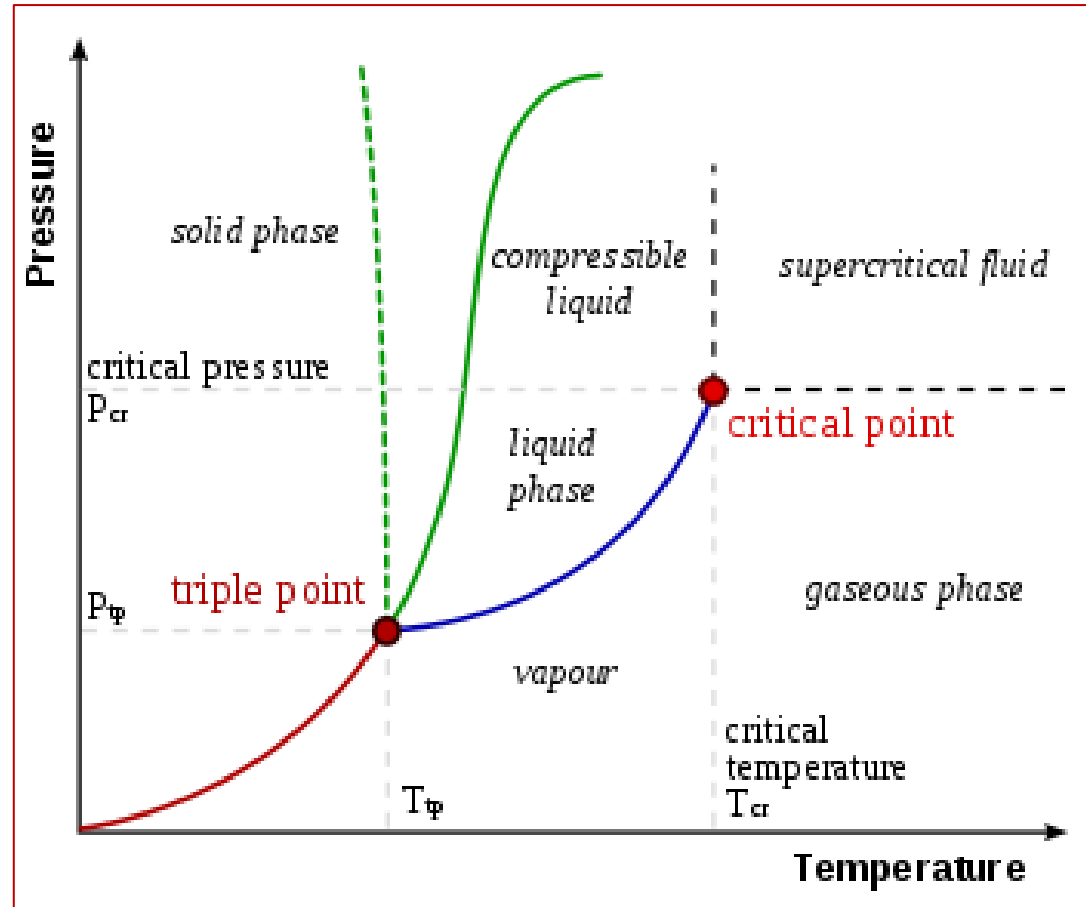
Sublimation is **the transition of a substance directly from a solid state to a gas state**.

Fusion is **the passage from the solid state to the liquid state** and it requires heat (energy) to take place

vaporization, **conversion of a substance from the liquid or solid phase into the gaseous (vapor) phase.**

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Sublimation:
Passing from the solid phase directly into the vapor phase.
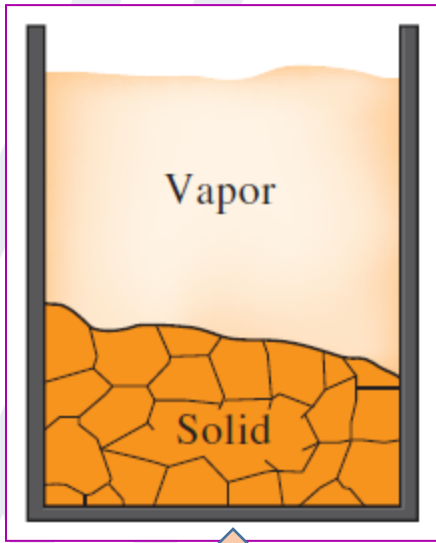
At low pressures (below the triple-point value), solids evaporate without melting first (sublimation).
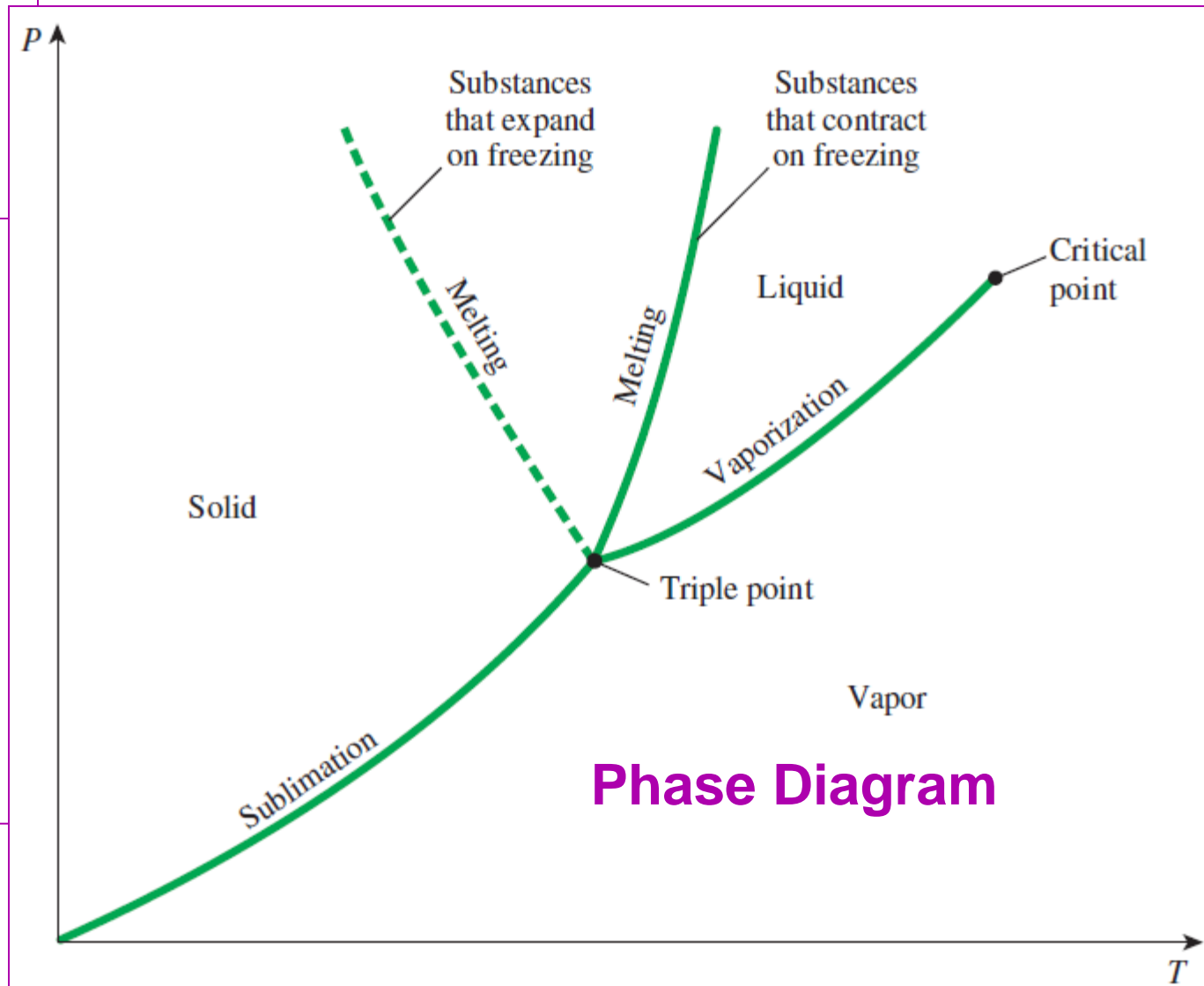
Phase Diagram

P-T **diagram of pure substances.**

4-5 PROPERTY TABLES

❑ **For most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations.**

❑ **Therefore, properties are frequently presented in the form of tables.**

❑ **Some thermodynamic properties can be measured easily, but others cannot and are calculated by using the relations between them and measurable properties.**

PROPERTY TABLES

- **The results of these measurements and calculations are presented in tables in a convenient format.**

Enthalpy—A Combination Property

$h = u + Pv$ $(\mathrm{kJ/kg})$ **specific Enthalpy**

$H = U + PV$ (kJ) **Total enthalpy**
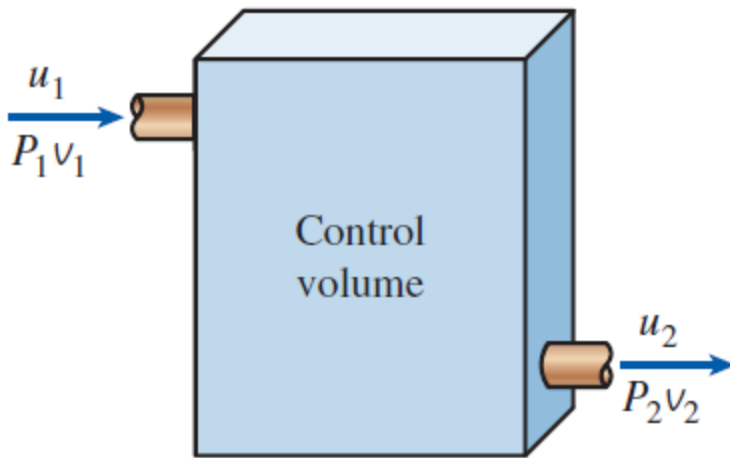
The
combination
$u + Pv$ **is**
frequently
encountered
in the
analysis of
control
volumes.

$$kPa{\cdot}m^3 \equiv kJ$$
$$kPa{\cdot}m^3/kg \equiv kJ/kg$$
$$bar{\cdot}m^3 \equiv 100 \ kJ$$
$$MPa{\cdot}m^3 \equiv 1000 \ kJ$$
$$psi{\cdot}ft^3 \equiv 0.18505 \ Btu$$

The product *pressure* × *volume* has energy units.

Temp., $T\,°C$	Sat. press., P_{sat} kPa	Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
205	1724.3	0.001164	0.11508	872.86	1723.5	2596.4	874.87	1920.0	2794.8	2.3776	4.0154	6.3930
210	1907.7	0.001173	0.10429	895.38	1702.9	2598.3	897.61	1899.7	2797.3	2.4245	3.9318	6.3563
215	2105.9	0.001181	0.094680	918.02	1681.9	2599.9	920.50	1878.8	2799.3	2.4712	3.8489	6.3200
220	2319.6	0.001190	0.086094	940.79	1660.5	2601.3	943.55	1857.4	2801.0	2.5176	3.7664	6.2840
225	2549.7	0.001199	0.078405	963.70	1638.6	2602.3	966.76	1835.4	2802.2	2.5639	3.6844	6.2483
230	2797.1	0.001209	0.071505	986.76	1616.1	2602.9	990.14	1812.8	2802.9	2.6100	3.6028	6.2128
235	3062.6	0.001219	0.065300	1010.0	1593.2	2603.2	1013.7	1789.5	2803.2	2.6560	3.5216	6.1775
240	3347.0	0.001229	0.059707	1033.4	1569.8	2603.1	1037.5	1765.5	2803.0	2.7018	3.4405	6.1424
245	3651.2	0.001240	0.054656	1056.9	1545.7	2602.7	1061.5	1740.8	2802.2	2.7476	3.3596	6.1072
250	3976.2	0.001252	0.050085	1080.7	1521.1	2601.8	1085.7	1715.3	2801.0	2.7933	3.2788	6.0721
255	4322.9	0.001263	0.045941	1104.7	1495.8	2600.5	1110.1	1689.0	2799.1	2.8390	3.1979	6.0369
260	4692.3	0.001276	0.042175	1128.8	1469.9	2598.7	1134.8	1661.8	2796.6	2.8847	3.1169	6.0017
265	5085.3	0.001289	0.038748	1153.3	1443.2	2596.5	1159.8	1633.7	2793.5	2.9304	3.0358	5.9662
270	5503.0	0.001303	0.035622	1177.9	1415.7	2593.7	1185.1	1604.6	2789.7	2.9762	2.9542	5.9305
275	5946.4	0.001317	0.032767	1202.9	1387.4	2590.3	1210.7	1574.5	2785.2	3.0221	2.8723	5.8944
280	6416.6	0.001333	0.030153	1228.2	1358.2	2586.4	1236.7	1543.2	2779.9	3.0681	2.7898	5.8579
285	6914.6	0.001349	0.027756	1253.7	1328.1	2581.8	1263.1	1510.7	2773.7	3.1144	2.7066	5.8210
290	7441.8	0.001366	0.025554	1279.7	1296.9	2576.5	1289.8	1476.9	2766.7	3.1608	2.6225	5.7834
295	7999.0	0.001384	0.023528	1306.0	1264.5	2570.5	1317.1	1441.6	2758.7	3.2076	2.5374	5.7450
300	8587.9	0.001404	0.021659	1332.7	1230.9	2563.6	1344.8	1404.8	2749.6	3.2548	2.4511	5.7059
305	9209.4	0.001425	0.019932	1360.0	1195.9	2555.8	1373.1	1366.3	2739.4	3.3024	2.3633	5.6657
310	9865.0	0.001447	0.018333	1387.7	1159.3	2547.1	1402.0	1325.9	2727.9	3.3506	2.2737	5.6243
315	10,556	0.001472	0.016849	1416.1	1121.1	2537.2	1431.6	1283.4	2715.0	3.3994	2.1821	5.5816
320	11,284	0.001499	0.015470	1445.1	1080.9	2526.0	1462.0	1238.5	2700.6	3.4491	2.0881	5.5372
325	12,051	0.001528	0.014183	1475.0	1038.5	2513.4	1493.4	1191.0	2684.3	3.4998	1.9911	5.4908
330	12,858	0.001560	0.012979	1505.7	993.5	2499.2	1525.8	1140.3	2666.0	3.5516	1.8906	5.4422
335	13,707	0.001597	0.011848	1537.5	945.5	2483.0	1559.4	1086.0	2645.4	3.6050	1.7857	5.3907
340	14,601	0.001638	0.010783	1570.7	893.8	2464.5	1594.6	1027.4	2622.0	3.6602	1.6756	5.3358
345	15,541	0.001685	0.009772	1605.5	837.7	2443.2	1631.7	963.4	2595.1	3.7179	1.5585	5.2765
350	16,529	0.001741	0.008806	1642.4	775.9	2418.3	1671.2	892.7	2563.9	3.7788	1.4326	5.2114
355	17,570	0.001808	0.007872	1682.2	706.4	2388.6	1714.0	812.9	2526.9	3.8442	1.2942	5.1384
360	18,666	0.001895	0.006950	1726.2	625.7	2351.9	1761.5	720.1	2481.6	3.9165	1.1373	5.0537
365	19,822	0.002015	0.006009	1777.2	526.4	2303.6	1817.2	605.5	2422.7	4.0004	0.9489	4.9493
370	21,044	0.002217	0.004953	1844.5	385.6	2230.1	1891.2	443.1	2334.3	4.1119	0.6890	4.8009
373.95	22,064	0.003106	0.003106	2015.7	0	2015.7	2084.3	0	2084.3	4.4070	0	4.4070

Source of Data: Tables A–4 through A–8 are generated using the Engineering

Saturated Liquid and Saturated Vapor States

V_f = specific volume of saturated liquid

V_g = speficic volume of saturated vapor

V_{fg} = difference between V_g and V_f (that is $V_{fg} = V_g - V_f$)

A partial list of Table A–4.

		Specific volume m³/kg	
Sat. Temp. °C T	Sat. press. kPa P_{sat}	Sat. liquid v_f	Sat. vapor v_g
85	57.868	0.001032	2.8261
90	70.183	0.001036	2.3593
95	84.609	0.001040	1.9808

Specific temperature

Corresponding saturation pressure

Specific volume of saturated liquid

Specific volume of saturated vapor

- **Table A–4: Saturation properties of water under temperature.**
- **Table A–5: Saturation properties of water under pressure.**

Enthalpy of vaporization, h_{fg} (Latent heat of vaporization): The amount of energy needed to vaporize a unit mass of saturated liquid at a given temperature or pressure.

EXAMPLE 4–1   Pressure of Saturated Liquid in a Tank

A rigid tank contains 50 kg of saturated liquid water at 90°C. Determine the pressure in the tank and the volume of the tank.

SOLUTION A rigid tank contains saturated liquid water. The pressure and volume of the tank are to be determined.

Analysis The state of the saturated liquid water is shown on a T-v diagram in Fig. 4–28. Since saturation conditions exist in the tank, the pressure must be the saturation pressure at 90°C:

$$P = P_{sat\ @\ 90°C} = 70.183\ \text{kPa} \quad (\text{Table A-4})$$

The specific volume of the saturated liquid at 90°C is

$$v = v_{f\ @\ 90°C} = 0.001036\ \text{m}^3/\text{kg} \quad (\text{Table A-4})$$

Then the total volume of the tank becomes

$$V = mv = (50\ \text{kg})(0.001036\ \text{m}^3/\text{kg}) = 0.0518\ \text{m}^3$$
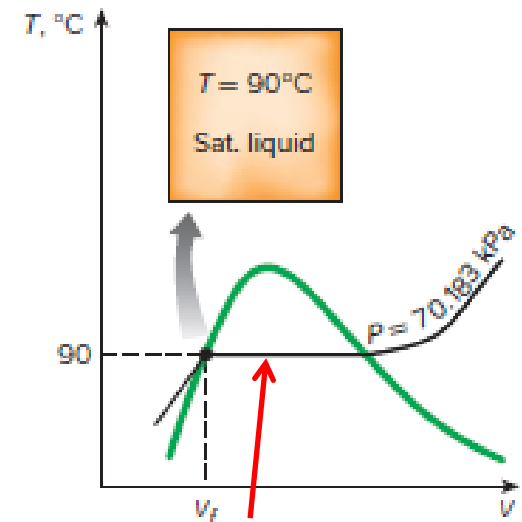

Statured Liquid line

FIGURE 4–28
Schematic and T-v diagram for Example 4–1.

TABLE A–4

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.609	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151

FIGURE 4–29

Schematic and *P-v* diagram for Example 4–2.

EXAMPLE 4–2 **Temperature of Saturated Vapor in a Cylinder**

A piston–cylinder device contains 2 ft³ of saturated water vapor at 50-psia pressure. Determine the temperature and the mass of the vapor inside the cylinder.

SOLUTION A cylinder contains saturated water vapor. The temperature and the mass of vapor are to be determined.

Analysis The state of the saturated water vapor is shown on a *P-v* diagram in Fig. 4–49. Since the cylinder contains saturated vapor at 50 psia, the temperature inside must be the saturation temperature at this pressure:

$$T = T_{\text{sat @ 50 psia}} = 280.99°F \quad \text{(Table A–5E)}$$

The specific volume of the saturated vapor at 50 psia is

$$v = v_{g \text{ @ 50 psia}} = 8.5175 \text{ ft}^3/\text{lbm} \quad \text{(Table A–5E)}$$

Then the mass of water vapor inside the cylinder becomes

$$m = \frac{V}{v} = \frac{2 \text{ ft}^3}{8.5175 \text{ ft}^3/\text{lbm}} = 0.235 \text{ lbm}$$

TABLE A–5E

Saturated water—Pressure table

| Press., P psia	Sat. temp., T_{sat} °F	Specific volume, ft³/lbm		Internal energy, Btu/lbm			Enthalpy, Btu/lbm			Entropy, Btu/lbm·R	
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}
1	101.69	0.01614	333.49	69.72	973.99	1043.7	69.72	1035.7	1105.4	0.13262	1.84495
2	126.02	0.01623	173.71	94.02	957.45	1051.5	94.02	1021.7	1115.8	0.17499	1.74444
3	141.41	0.01630	118.70	109.39	946.90	1056.3	109.40	1012.8	1122.2	0.20090	1.68489
4	152.91	0.01636	90.629	120.89	938.97	1059.9	120.90	1006.0	1126.9	0.21985	1.64225
5	162.18	0.01641	73.525	130.17	932.53	1062.7	130.18	1000.5	1130.7	0.23488	1.60894
6	170.00	0.01645	61.982	138.00	927.08	1065.1	138.02	995.88	1133.9	0.24739	1.58155
8	182.81	0.01652	47.347	150.83	918.08	1068.9	150.86	988.15	1139.0	0.26757	1.53800
10	193.16	0.01659	38.425	161.22	910.75	1072.0	161.25	981.82	1143.1	0.28362	1.50391
14.696	211.95	0.01671	26.805	180.12	897.27	1077.4	180.16	970.12	1150.3	0.31215	1.44441
15	212.99	0.01672	26.297	181.16	896.52	1077.7	181.21	969.47	1150.7	0.31370	1.44441
20	227.92	0.01683	20.093	196.21	885.63	1081.8	196.27	959.93	1156.2	0.33582	1.39606
25	240.03	0.01692	16.307	208.45	876.67	1085.1	208.52	952.03	1160.6	0.35347	1.36060
30	250.30	0.01700	13.749	218.84	868.98	1087.8	218.93	945.21	1164.1	0.36821	1.33132
35	259.25	0.01708	11.901	227.92	862.19	1090.1	228.03	939.16	1167.2	0.38093	1.30632
40	267.22	0.01715	10.501	236.02	856.09	1092.1	236.14	933.69	1169.8	0.39213	1.28448
45	274.41	0.01721	9.4028	243.34	850.52	1093.9	243.49	928.68	1172.2	0.40216	1.26506
50	280.99	0.01727	8.5175	250.05	845.39	1095.4	250.21	924.03	1174.2	0.41125	1.24756
55	287.05	0.01732	7.7882	256.25	840.61	1096.9	256.42	919.70	1176.1	0.41958	1.23162
60	292.69	0.01738	7.1766	262.01	836.13	1098.1	262.20	915.61	1177.8	0.42728	1.21697
65	297.95	0.01743	6.6560	267.41	831.90	1099.3	267.62	911.75	1179.4	0.43443	1.20341
70	302.91	0.01748	6.2075	272.50	827.90	1100.4	272.72	908.08	1180.8	0.44112	1.19078
75	307.59	0.01752	5.8167	277.31	824.09	1101.4	277.55	904.58	1182.1	0.44741	1.17895
80	312.02	0.01757	5.4733	281.87	820.45	1102.3	282.13	901.22	1183.4	0.45335	1.16783
85	316.24	0.01761	5.1689	286.22	816.97	1103.2	286.50	898.00	1184.5	0.45897	1.15732
90	320.26	0.01765	4.8972	290.38	813.62	1104.0	290.67	894.89	1185.6	0.46431	1.14737
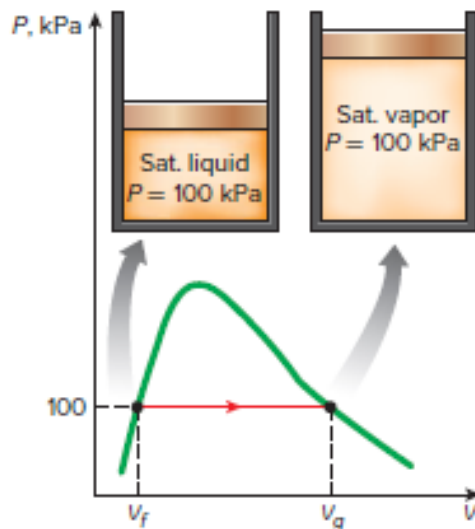
FIGURE 4–30
Schematic and P-v diagram for Example 4–3.

EXAMPLE 4–3   **Volume and Energy Change during Evaporation**

A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 100 kPa. Determine (a) the volume change and (b) the amount of energy transferred to the water.

SOLUTION Saturated liquid water is vaporized at constant pressure. The volume change and the energy transferred are to be determined.

Analysis (a) The process described is illustrated on a P-v diagram in Fig. 4–30. The volume change per unit mass during a vaporization process is v_{fg}, which is the difference between v_g and v_f. Reading these values from Table A–5 at 100 kPa and substituting yield

$$v_{fg} = v_g - v_f = 1.6941 - 0.001043 = 1.6931 \text{ m}^3/\text{kg}$$

Thus,

$$\Delta V = m v_{fg} = (0.2 \text{ kg})(1.6931 \text{ m}^3/\text{kg}) = \mathbf{0.3386 \text{ m}^3}$$

(b) The amount of energy needed to vaporize a unit mass of a substance at a given pressure is the enthalpy of vaporization at that pressure, which is $h_{fg} = 2257.5$ kJ/kg for water at 100 kPa. Thus, the amount of energy transferred is

$$m h_{fg} = (0.2 \text{ kg})(2257.5 \text{ kJ/kg}) = \mathbf{451.5 \text{ kJ}}$$

Discussion Note that we have considered the first four decimal digits of v_{fg} and disregarded the rest. This is because v_g has significant numbers to the first four decimal places only, and we do not know the numbers in the other decimal places. Copying all the digits from the calculator would mean that we are assuming $v_g = 1.694100$, which is not necessarily the case. It could very well be that $v_g = 1.694138$ since this number, too, would truncate to 1.6941. All the digits in our result (1.6931) are significant. But if we did not truncate the result, we would obtain $v_{fg} = 1.693057$, which falsely implies that our result is accurate to the sixth decimal place.

TABLE A-5

Saturated water—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931
75	91.76	0.001037	2.2172	384.36	2111.8	2496.1	384.44	2278.0	2662.4	1.2132	6.2426	7.4558
100	99.61	0.001043	1.6941	417.40	2088.2	2505.6	417.51	2257.5	2675.0	1.3028	6.0562	7.3589
101.325	99.97	0.001043	1.6734	418.95	2087.0	2506.0	419.06	2256.5	2675.6	1.3069	6.0476	7.3545
125	105.97	0.001048	1.3750	444.23	2068.8	2513.0	444.36	2240.6	2684.9	1.3741	5.9100	7.2841
150	111.35	0.001053	1.1594	466.97	2052.3	2519.2	467.13	2226.0	2693.1	1.4337	5.7894	7.2231

Examples: Saturated liquid and saturated vapor states of water on *T-v* and *P-v* diagrams.
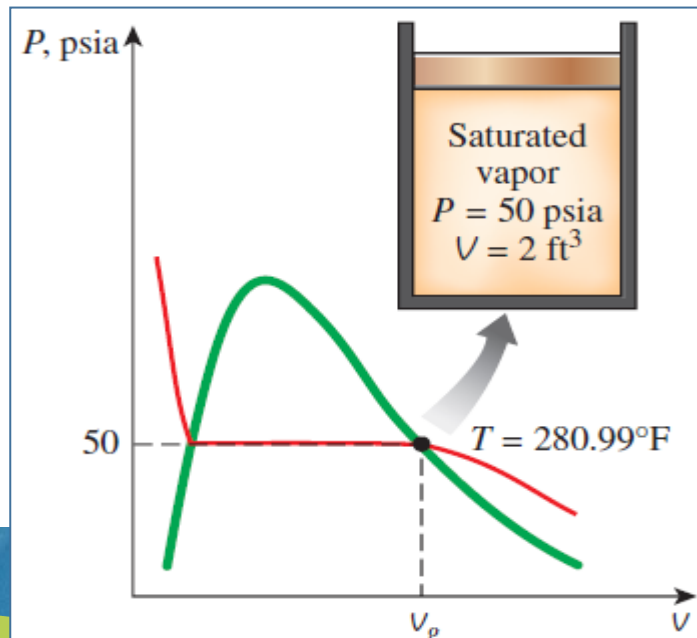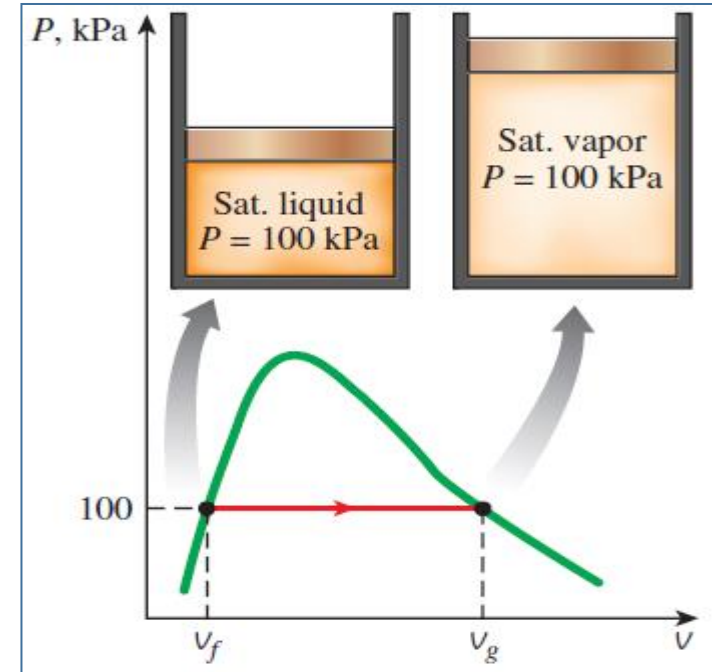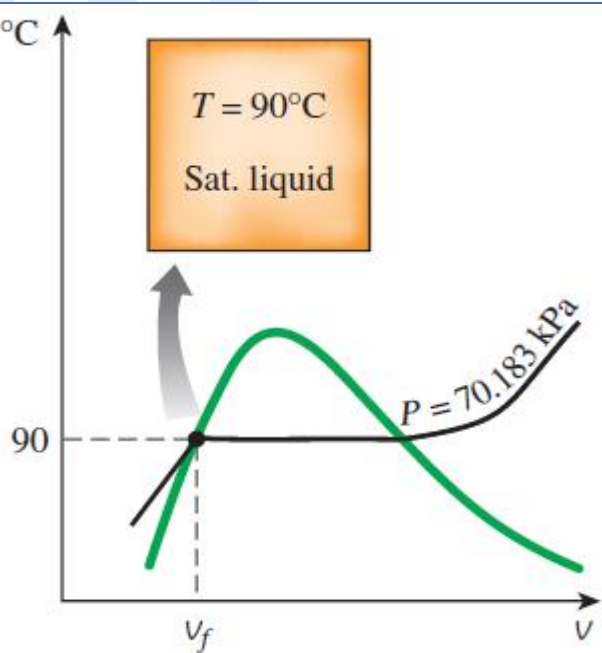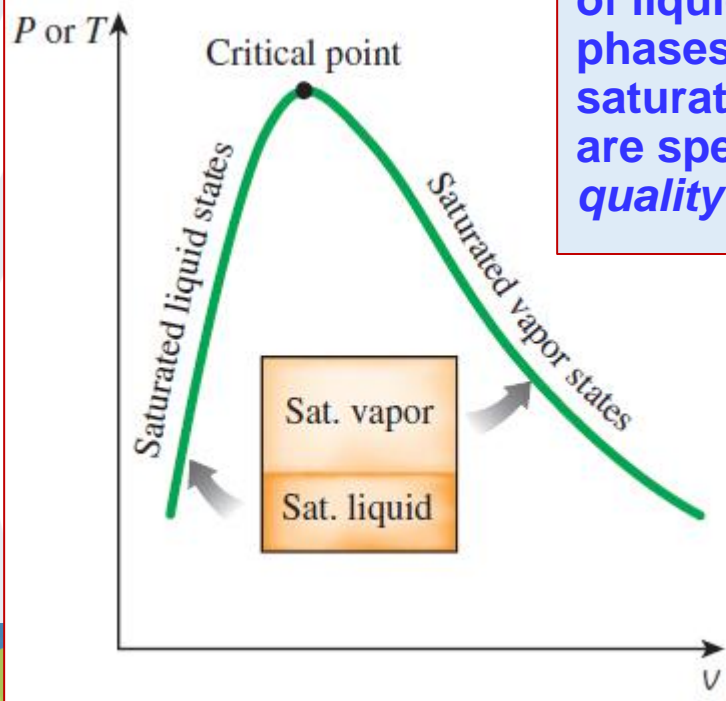
Saturated Liquid–Vapor Mixture

Quality, x : The ratio of the mass of vapor to the total mass of the mixture. Quality is between 0 and 1 → 0: sat. liquid, 1: sat. vapor.

The properties of the saturated liquid are the same whether it exists alone or in a mixture with saturated vapor.
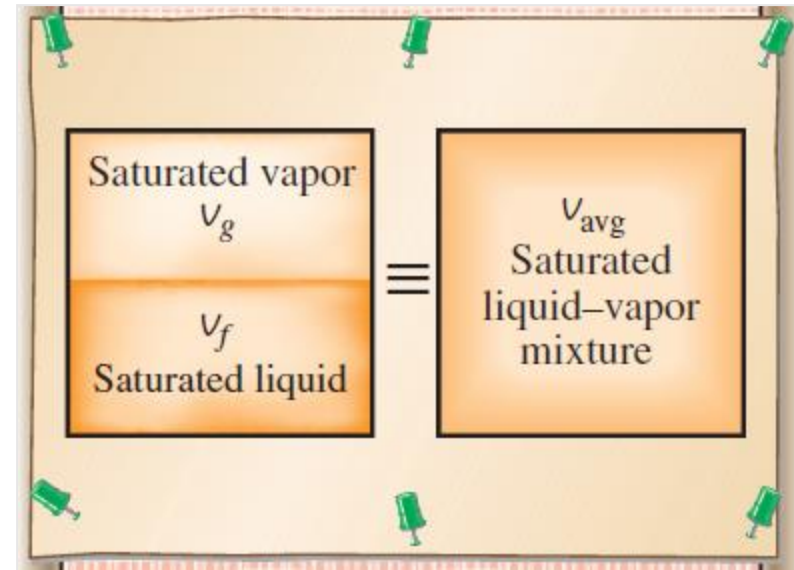
$$x = \frac{m_{\text{vapor}}}{m_{\text{total}}} \qquad m_{\text{total}} = m_{\text{liquid}} + m_{\text{vapor}} = m_f + m_g$$

Temperature and pressure are dependent properties for a mixture.

The relative amounts of liquid and vapor phases in a saturated mixture are specified by the *quality x.*

A two-phase system can be treated as a homogeneous mixture for convenience.

$$V_{avg} = V_f + X V_{fg} \quad (\text{m}^3/\text{kg})$$

$$x = m_g / m_t$$

$$x = \frac{V_{avg} - V_f}{V_{fg}}$$

$$u_{avg} = u_f + x u_{fg} \quad (\text{KJ/kg})$$

$$h_{avg} = h_f + x h_{fg} \quad (\text{KJ/kg})$$

FIGURE 4-33

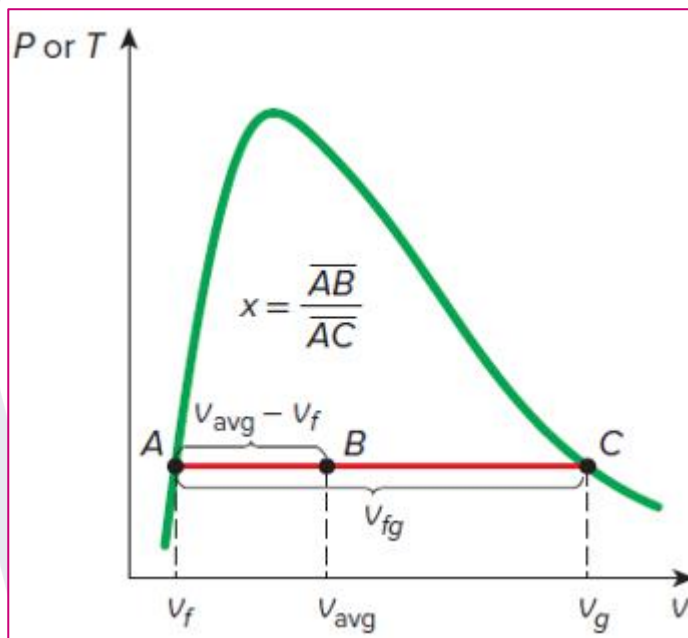**Quality is related to the horizontal distances on *P-v* and *T-v* diagrams.**

At a given temperature or pressure, the numerator of Eq. is the distance between the actual state and the saturated liquid state, and the denominator is the length of the entire horizontal line that connects the saturated liquid and saturated vapor states. A state of 50 percent quality lies in the middle of this horizontal line.

Saturated Liquid–Vapor Mixture

$y \rightarrow v, u,$ *or* $h.$

$$y_{\text{avg}} = y_f + x y_{fg}$$

$$y_f \leq y_{\text{avg}} \leq y_g$$
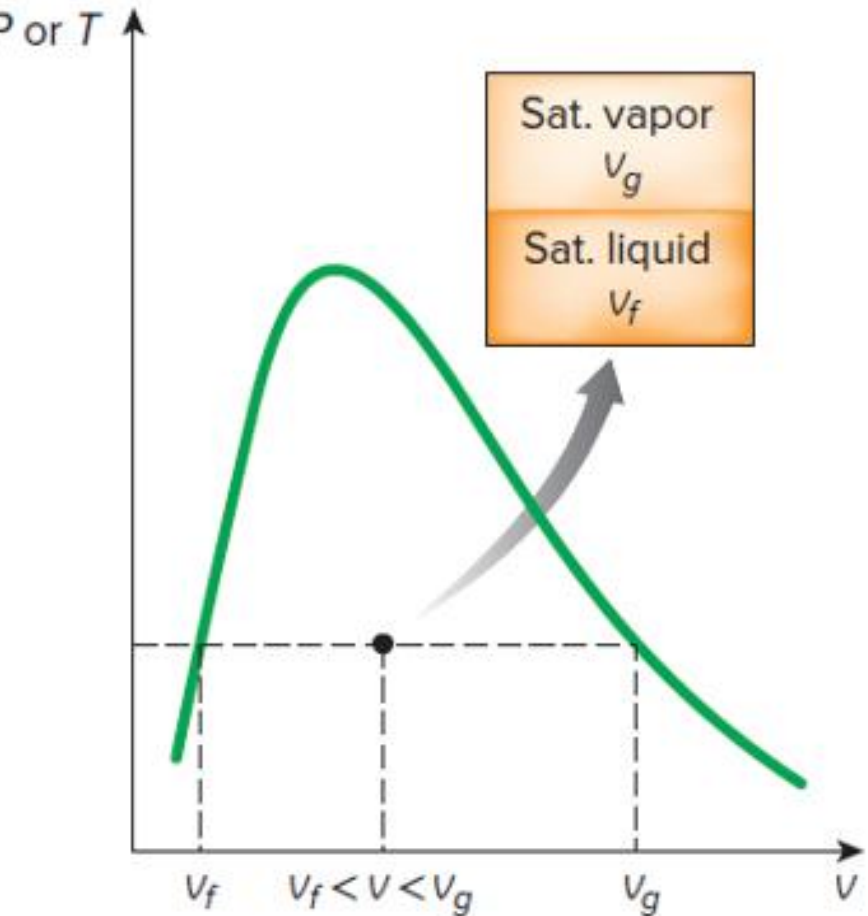
where *y* is *v*, *u,* or *h*. The subscript "avg" (for "average") is usually dropped for simplicity.

FIGURE 4-34

The *v value of a saturated liquid-vapor mixture lies between the* v_f *and* v_g *values at the specified T or P*

Examples: Saturated liquid-vapor mixture states on *T-v* and *P-v* diagrams.

EXAMPLE 4–4 Pressure and Volume of a Saturated Mixture

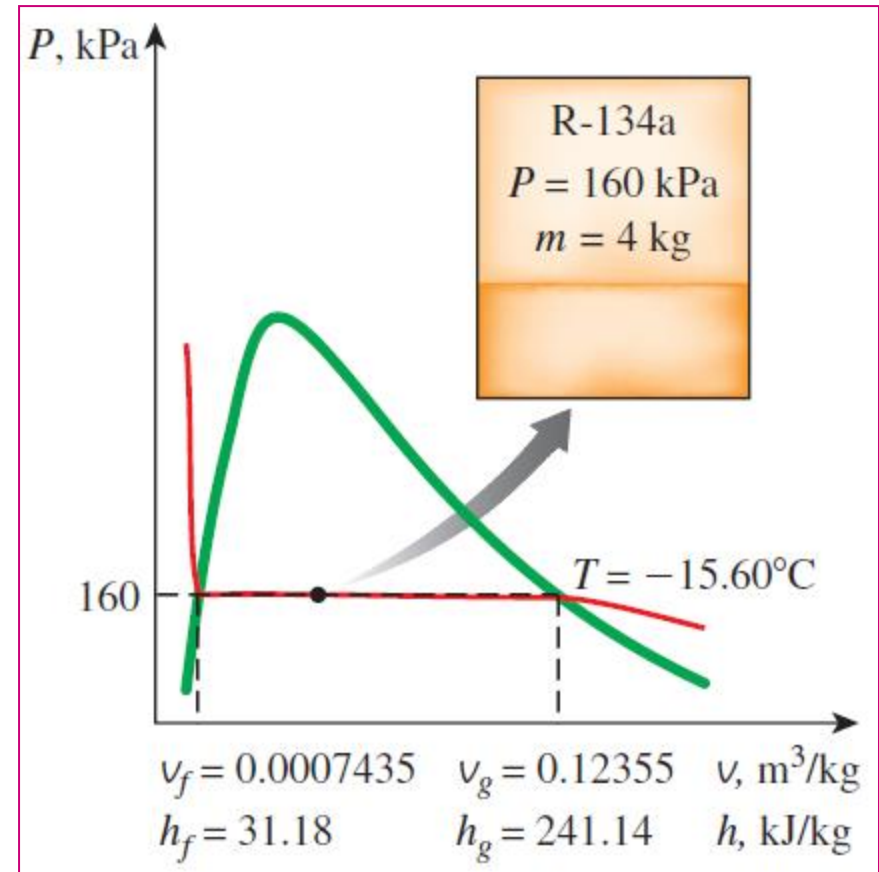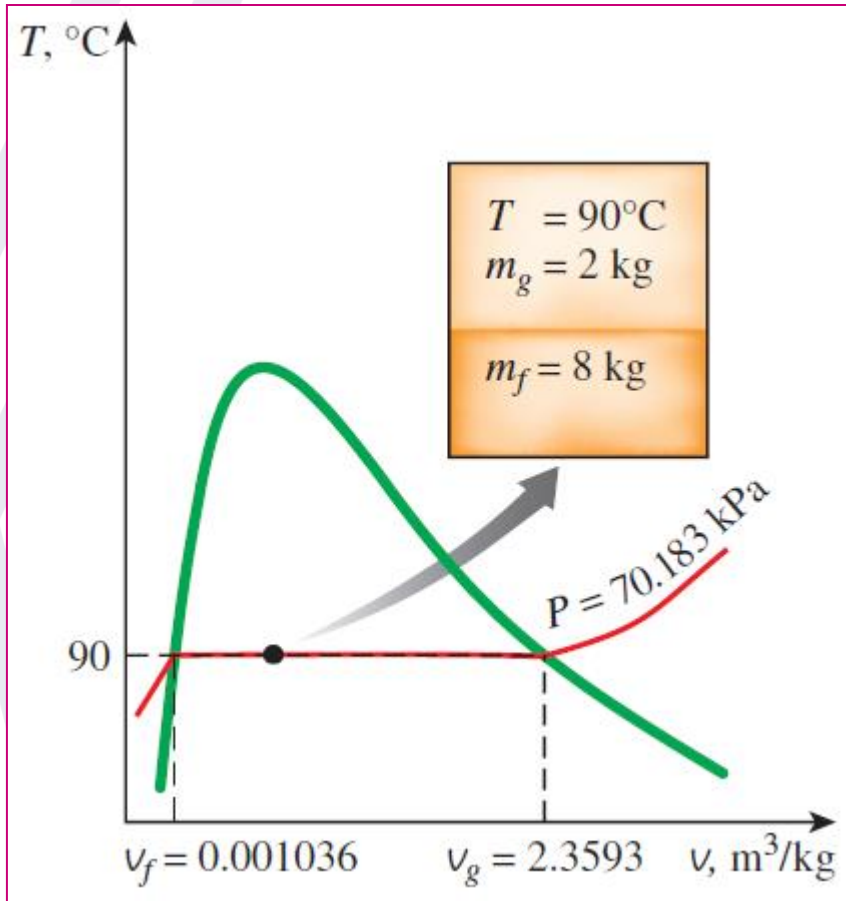A rigid tank contains 10 kg of water at 90°C. If 8 kg of the water is in the liquid form and the rest is in the vapor form, determine (a) the pressure in the tank and (b) the volume of the tank.

SOLUTION

A rigid tank contains saturated mixture. The pressure and the volume of the tank are to be determined.

Analysis

(a) The state of the saturated liquid–vapor mixture is shown in **Fig. 4–35**. Since the two phases coexist in equilibrium, we have a saturated mixture, and the pressure must be the saturation pressure at the given temperature:

$$P = P_{sat @ 90°C} = 70.183 \text{ kPa} \quad \text{(Table A–4)}$$
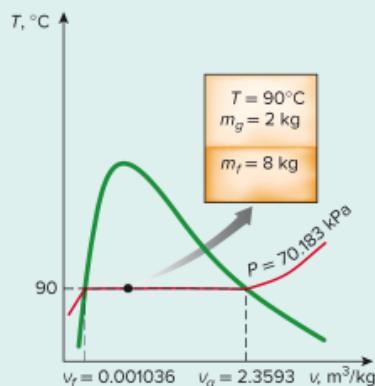
FIGURE 4–35
Schematic and *T-v* diagram for **Example 4–4**.

(b) At 90°C, we have $v_f = 0.001036 \text{ m}^3/\text{kg}$ and $v_g = 2.3593 \text{ m}^3/\text{kg}$ (**Table A–4**). One way of finding the volume of the tank is to determine the volume occupied by each phase and then add them:

$$V = V_f + V_g = m_f v_f + m_g v_g$$
$$= (8 \text{ kg})(0.001036 \text{ m}^3/\text{kg}) + (2 \text{ kg})(2.3593 \text{ m}^3/\text{kg})$$
$$= 4.73 \text{ m}^3$$

Another way is to first determine the quality x, then the average specific volume v, and finally the total volume:

$$x = \frac{m_g}{m_t} = \frac{2 \text{ kg}}{10 \text{ kg}} = 0.2$$

$$v = v_f + x v_{fg}$$
$$= 0.001036 \text{ m}^3/\text{kg} + (0.2)[(2.3593 - 0.001036) \text{ m}^3/\text{kg}]$$
$$= 0.473 \text{ m}^3/\text{kg}$$

and

$$V = mv = (10 \text{ kg})(0.473 \text{ m}^3/\text{kg}) = 4.73 \text{ m}^3$$

Discussion

The first method appears to be easier in this case since the masses of each phase are given. In most cases, however, the masses of each phase are not available, and the second method becomes more convenient.

TABLE A–4

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.352	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.763	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.947	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.043	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.202	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.597	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.416	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.868	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.183	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.609	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151
100	101.42	0.001043	1.6720	419.06	2087.0	2506.0	419.17	2256.4	2675.6	1.3072	6.0470	7.3542

Example 4-5

EXAMPLE 4–5   Properties of Saturated Liquid–Vapor Mixture

An 80-L vessel contains 4 kg of refrigerant-134a at a pressure of 160 kPa. Determine (a) the temperature, (b) the quality, (c) the enthalpy of the refrigerant, and (d) the volume occupied by the vapor phase.

SOLUTION   A vessel is filled with refrigerant-134a. Some properties of the refrigerant are to be determined.
Analysis   (a) The state of the saturated liquid–vapor mixture is shown in Fig. 4–36. At this point we do not know whether the refrigerant is in the compressed liquid or saturated mixture region. This can be determined by comparing a suitable property to the saturated liquid and saturated vapor values. From the information given, we can determine the specific volume:

$$v = \frac{V}{m} = \frac{0.080 \text{ m}^3}{4 \text{ kg}} = 0.02 \text{ m}^3\text{/kg}$$

At 160 kPa, we read

$$v_f = 0.0007435 \text{ m}^3\text{/kg}$$
$$v_g = 0.12355 \text{ m}^3\text{/kg} \qquad \text{(Table A–12)}$$

Obviously, $v_f < v < v_g$, and, the refrigerant is in the saturated mixture region. Thus, the temperature must be the saturation temperature at the specified pressure:

$$T = T_{\text{sat @ 160 kPa}} = -15.60°C$$

(b) Quality can be determined from

$$x = \frac{v - v_f}{v_{fg}} = \frac{0.02 - 0.0007435}{0.12355 - 0.0007435} = 0.157$$

(c) At 160 kPa, we also read from Table A–12 that $h_f = 31.18$ kJ/kg and $h_{fg} = 209.96$ kJ/kg. Then,

$$h = h_f + xh_{fg}$$
$$= 31.18 \text{ kJ/kg} + (0.157)(209.96 \text{ kJ/kg})$$
$$= 64.1 \text{ kJ/kg}$$

FIGURE 4–35
Schematic and *T-v* diagram
for Example 4–4.

$$v_f = 0.0007435 \quad v_g = 0.12355 \quad v, \text{ m}^3\text{/kg}$$
$$h_f = 31.18 \qquad h_g = 241.14 \quad h, \text{ kJ/kg}$$
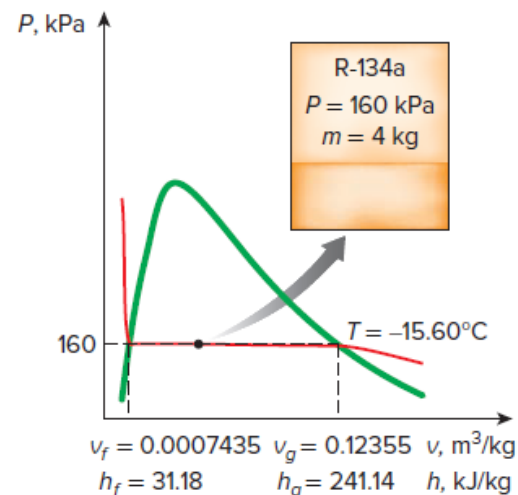
FIGURE 4–36
Schematic and *P-v* diagram
for Example 4–5.

(d) The mass of the vapor is

$$m_g = xm_t = (0.157)(4 \text{ kg}) = 0.628 \text{ kg}$$

and the volume occupied by the vapor phase is

$$V_g = m_g v_g = (0.628 \text{ kg})(0.12355 \text{ m}^3\text{/kg}) = 0.0776 \text{ m}^3 \text{ (or 77.6 L)}$$

The rest of the volume (2.4 L) is occupied by the liquid.

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TABLE A–12

Saturated refrigerant-134a—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
60	−36.95	0.0007097	0.31108	3.795	205.34	209.13	3.837	223.96	227.80	0.01633	0.94812	0.96445
70	−33.87	0.0007143	0.26921	7.672	203.23	210.90	7.722	222.02	229.74	0.03264	0.92783	0.96047
80	−31.13	0.0007184	0.23749	11.14	201.33	212.48	11.20	220.27	231.47	0.04707	0.91009	0.95716
90	−28.65	0.0007222	0.21261	14.30	199.60	213.90	14.36	218.67	233.04	0.06003	0.89431	0.95434
100	−26.37	0.0007258	0.19255	17.19	198.01	215.21	17.27	217.19	234.46	0.07182	0.88008	0.95191
120	−22.32	0.0007323	0.16216	22.38	195.15	217.53	22.47	214.52	236.99	0.09269	0.85520	0.94789
140	−18.77	0.0007381	0.14020	26.96	192.60	219.56	27.06	212.13	239.19	0.11080	0.83387	0.94467
160	−15.60	0.0007435	0.12355	31.06	190.31	221.37	31.18	209.96	241.14	0.12686	0.81517	0.94202
180	−12.73	0.0007485	0.11049	34.81	188.20	223.01	34.94	207.95	242.90	0.14131	0.79848	0.93979
200	−10.09	0.0007532	0.099951	38.26	186.25	224.51	38.41	206.09	244.50	0.15449	0.78339	0.93788

Superheated Vapor

In the region to the right of the saturated vapor line and at temperatures above the critical point temperature, a substance exists as superheated vapor.
In this region, temperature and pressure are independent properties.

$T,°C$	v m³/kg	u kJ/kg	h kJ/kg
	$P = 0.1$ MPa (99.61°C)		
Sat.	1.6941	2505.6	2675.0
100	1.6959	2506.2	2675.8
150	1.9367	2582.9	2776.6
⋮	⋮	⋮	⋮
1300	7.2605	4687.2	5413.3
	$P = 0.5$ MPa (151.83°C)		
Sat.	0.37483	2560.7	2748.1
200	0.42503	2643.3	2855.8
250	0.47443	2723.8	2961.0

A partial listing of Table A–6.

Superheated Vapor

Compared to saturated vapor, **superheated** vapor is characterized by

Lower pressures $(P < P_{\text{sat}}$ at a given $T)$

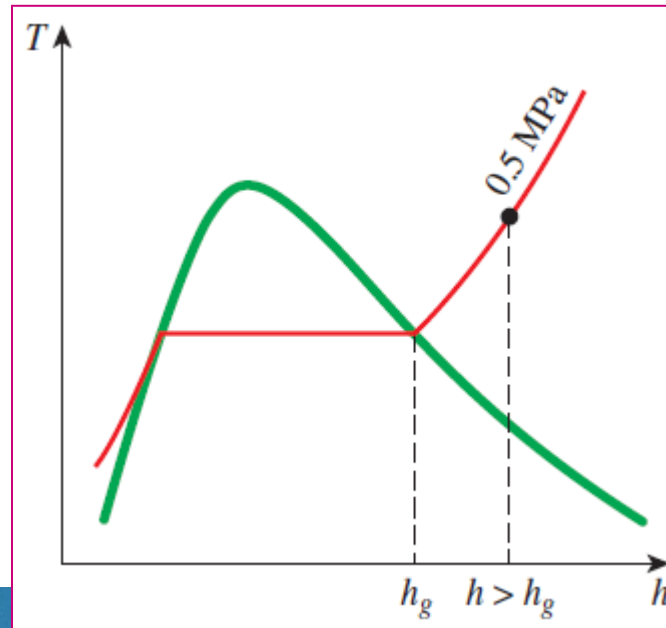**Higher temperatures** $(T > T_{\text{sat}}$ at a given $P)$
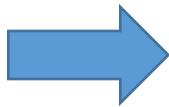
Higher specific volumes $(v > v_g$ at a given P or $T)$

Higher internal energies $(u > u_g$ at a given P or $T)$

Higher enthalpies $(h > h_g$ at a given P or $T)$

- Saturated vapor: A vapor that is about to condense.
- Superheated vapor: A vapor that is not about to condense

At a specified P, superheated vapor exists at a higher h than the saturated vapor.

Compressed Liquid

The compressed liquid properties depend on temperature much more strongly than they do on pressure.

$$y \cong y_{f@T} \qquad y \rightarrow v, u, \text{ or } h$$

A more accurate relation for h

$$h \cong h_{f@T} + V_{f@T}(P - P_{sat@T})$$

Compressed liquid is characterized by

Higher pressures $(P > P_{sat}$ at a given $T)$

Lower temperatures $(T < T_{sat}$ at a given $P)$

Lower specific volumes $(v < v_f$ at a given P or $T)$

Lower internal energies $(u < u_f$ at a given P or $T)$

Lower enthalpies $(h < h_f$ at a given P or $T)$

- **Given: P and T**

  - $v \cong v_{f@T}$

  - $u \cong u_{f@T}$

  - $h \cong h_{f@T}$

A compressed liquid may be approximated as a saturated liquid at the given temperature.

T, °C

$T = 80°C$
$P = 5$ MPa

5 MPa

80

$u \cong u_{f@80°C}$

u
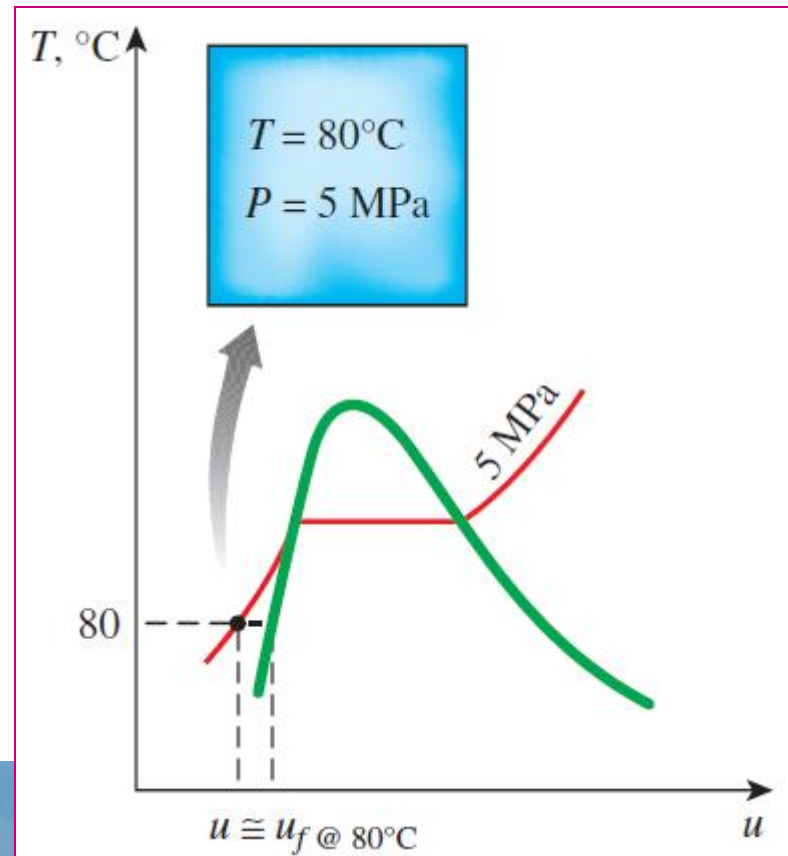
Reference State and Reference Values

- The values of *u, h,* and *s* cannot be measured directly, and they are calculated from measurable properties using the relations between properties.

- However, those relations give the *changes* in properties, not the values of properties at specified states.

- Therefore, we need to choose a convenient *reference state* and assign a value of *zero* for a convenient property or properties at that state.

- The reference state for water is $0.01°C$ and for R-134a is $-40°C$ in tables.

- Some properties may have negative values as a result of the reference state chosen.

- Sometimes different tables list different values for some properties at the same state as a result of using a different reference state.

- However, In thermodynamics we are concerned with the *changes* in properties, and the reference state chosen is of no consequence in calculations.

Reference State and Reference Values

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249

Saturated refrigerant-134a—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
−40	51.25	0.0007054	0.36081	−0.036	207.40	207.37	0.000	225.86	225.86	0.00000	0.96866	0.96866

4-6 THE IDEAL-GAS EQUATION OF STATE

- **Equation of state**: Any equation that relates the pressure, temperature, and specific volume of a substance.
- The simplest and best-known equation of state for substances in the gas phase is the ideal-gas equation of state. This equation predicts the *P-v-T* behavior of a gas quite accurately within some properly selected region.

$$P = R\left(\frac{T}{V}\right)$$

$$Pv = RT$$

Ideal gas equation of state

$$R = \frac{R_u}{M} \quad (\text{kJ/kg.K or kPa.m}^3/\text{kg.K})$$

R: gas constant
M: molar mass(kg/kmol)
R_u: universal gas constant

$$R_u = \begin{cases} 8.31447 \ \text{kJ/kmol.K} \\ 8.31447 \ \text{kPa.m}^3/\text{kmol.K} \\ 0.0831447 \ \text{bar.m}^3/\text{kmol.K} \\ 1.98588 \ \text{Btu/lbmol.R} \\ 10.7316 \ \text{psia.m}^3/\text{lbmol.R} \\ 1545.37 \ \text{ft.lbf/lbmol.R} \end{cases}$$

Substance	R, kJ/kg·K
Air	0.2870
Helium	2.0769
Argon	0.2081
Nitrogen	0.2968

Different substances have different gas constants.

Mass = Molar mass × Mole number

$$m = MN \quad \text{(Kg)}$$

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Ideal gas equation at two states for a fixed mass
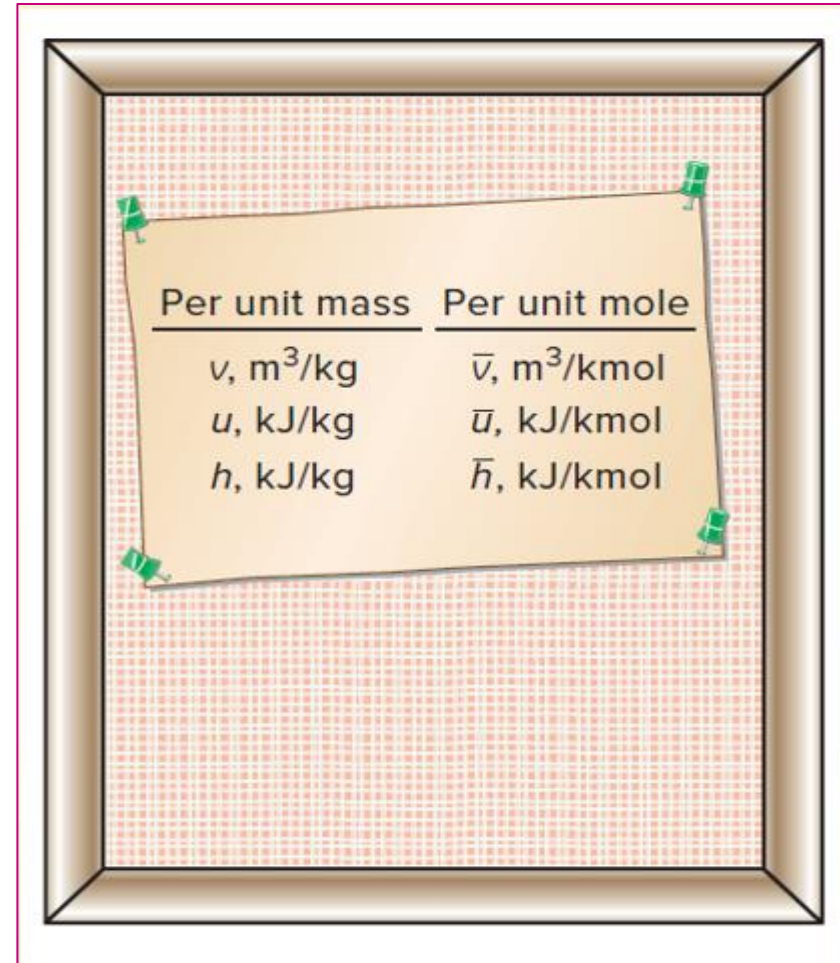
Various expressions of ideal gas equation

$$V = mv \rightarrow PV = mRT$$

$$mR = (MR)R = NR_u \rightarrow PV = NR_u T$$

$$V = N\bar{V} \rightarrow P\bar{V} = R_u T$$

Per unit mass	Per unit mole
v, m^3/kg	$\bar{v}$, m^3/kmol
u, kJ/kg	$\bar{u}$, kJ/kmol
h, kJ/kg	$\bar{h}$, kJ/kmol

Real gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).

FIGURE 4-43

Properties per unit mole are denoted with a bar on the top.

Is Water Vapor an Ideal Gas?
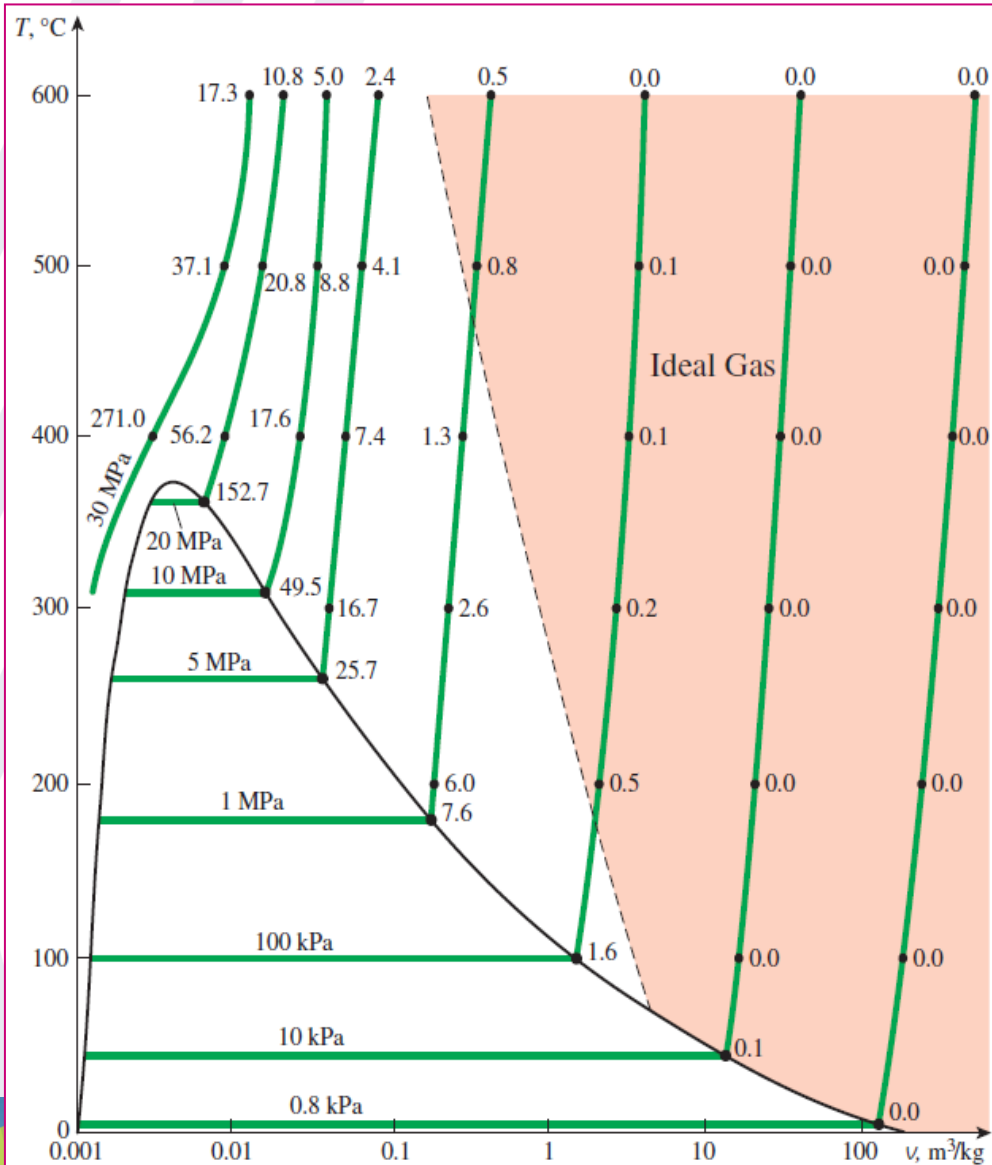
At pressures below 10 kPa, water vapor can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1 percent).

At higher pressures, however, the ideal gas assumption yields unacceptable errors, particularly in the vicinity of the critical point and the saturated vapor line.

In air-conditioning applications, the water vapor in the air can be treated as an ideal gas. Why?

Because; in air-conditioning applications, the water vapor in the air can be treated as an ideal gas with essentially no error since the pressure of the water vapor is very low

In steam power plant applications, however, the pressures involved are usually very high; therefore, ideal-gas relations should not be used.

Percentage of error
$$([|V_{table} - V_{ideal}|/V_{table}] \times 100)$$

involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with less than 1 percent error.

4-7 COMPRESSIBILITY FACTOR—A MEASURE OF DEVIATION FROM IDEAL-GAS BEHAVIOR

Compressibility factor *Z* A factor that accounts for the deviation of real gases from ideal-gas behavior at a given temperature and pressure.

$$Pv = ZRT$$

$$Z = \frac{PV}{RT} \qquad Z = \frac{V_{actual}}{V_{ideal}}$$

The farther away *Z* is from unity, the more the gas deviates from ideal-gas behavior.

Gases behave as an ideal gas at low densities (i.e., low pressure, high temperature).

Question: What is the criteria for low pressure and high temperature?

Answer: The pressure or temperature of a gas is high or low relative to its critical temperature or pressure.

Ideal gas $Z = 1$

Real gases $Z \begin{cases} > 1 \\ = 1 \\ < 1 \end{cases}$

Real gas — as $P \to 0$ → Ideal gas

- **FIGURE 4-46**
- **The compressibility factor is unity for ideal gases.**
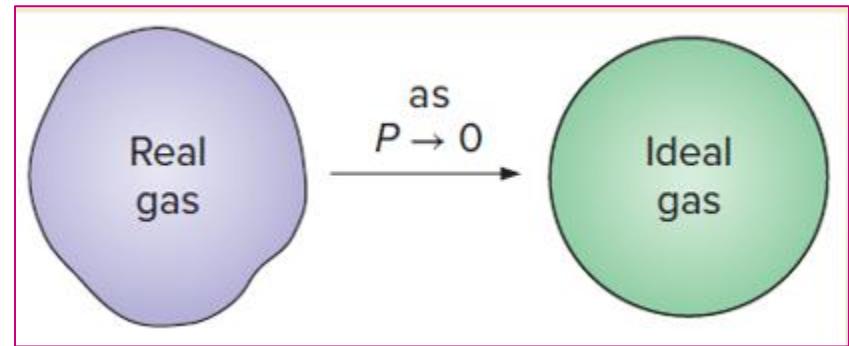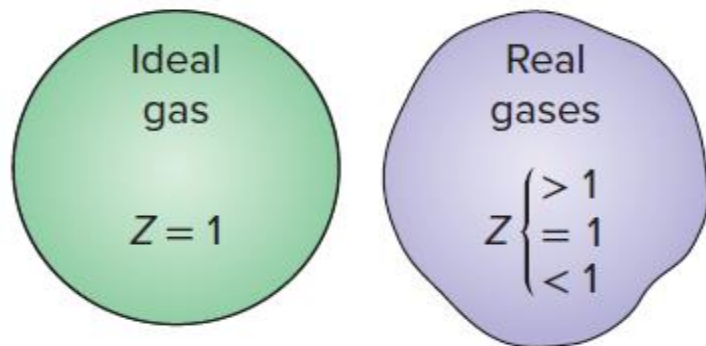
FIGURE 4-46

At very low pressures, all gases approach ideal-gas behavior (regardless of their temperature)

$$P_R = \frac{P}{P_{cr}} \qquad T_R = \frac{T}{T_{cr}}$$

Reduced pressure **Reduced temperature**

4-7 Compressibility Factor—a Measure Of Deviation From Ideal-gas Behavior-1

$$\left. \begin{array}{c} P_R = \dfrac{P}{P_{cr}} \\[2em] V_R = \dfrac{V}{RT_{cr}/P_{cr}} \end{array} \right\} \begin{array}{l} Z = \ldots \\ \text{(Fig. A–28)} \end{array}$$

$$V_R = \frac{V_{actual}}{RT_{cr}/P_{cr}}$$ **Pseudo-reduced specific volume**

Z can also be determined from a knowledge of P_R and V_R.
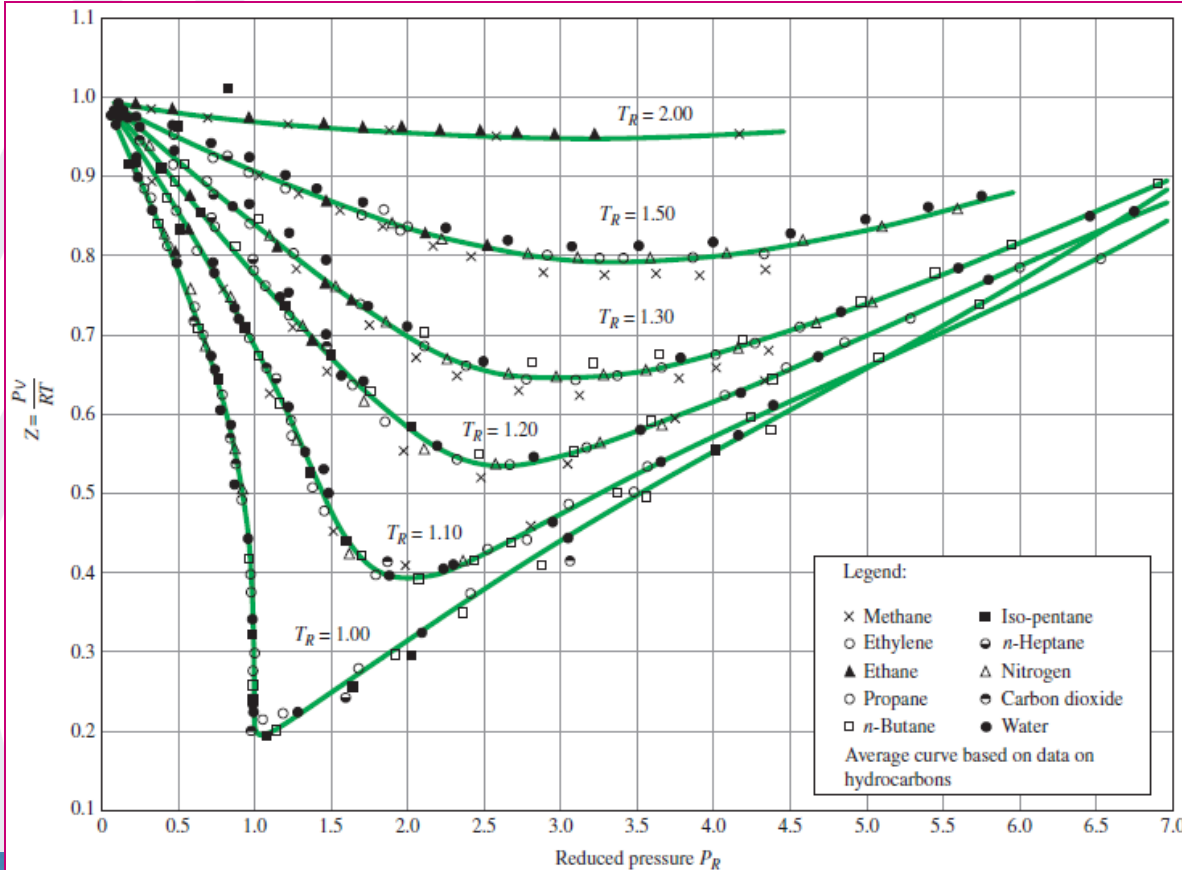
Comparison of Z factors for various gases.
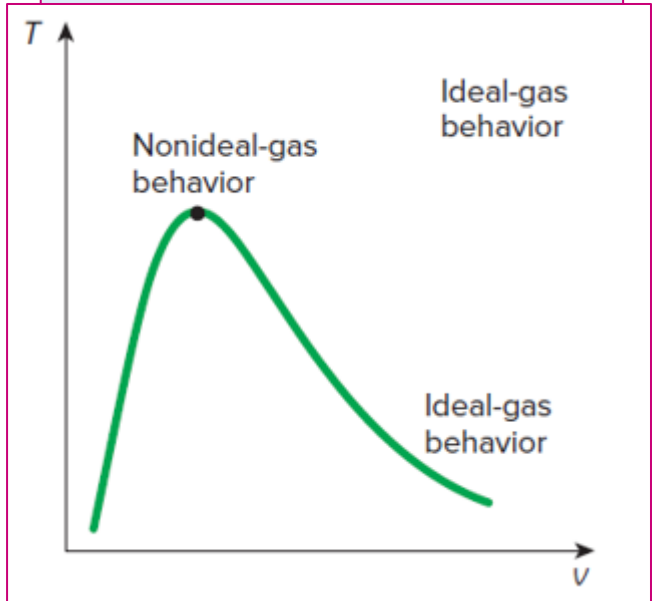
- **FIGURE 4-49**
- **Gases deviate from the ideal-gas behavior the most in the neighborhood of the critical point.**

Summary

Pure substance

Phases of a pure substance

Phase-change processes of pure substances
- Compressed liquid, Saturated liquid, Saturated vapor, Superheated vapor
- Saturation temperature and Saturation pressure

Property diagrams for phase change processes
- The *T-v* diagram, The *P-v* diagram, The *P-T* diagram, *The P-v-T* surface

Property tables
- Enthalpy
- Saturated liquid, saturated vapor, Saturated liquid vapor mixture, Superheated vapor, compressed liquid
- Reference state and reference values

The ideal gas equation of state
- Is water vapor an ideal gas?

Compressibility factor

Temp., $T\,°C$	Sat. press., P_{sat} kPa	Specific volume, m³/kg Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, kJ/kg Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Entropy, kJ/kg·K Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
205	1724.3	0.001164	0.11508	872.86	1723.5	2596.4	874.87	1920.0	2794.8	2.3776	4.0154	6.3930
210	1907.7	0.001173	0.10429	895.38	1702.9	2598.3	897.61	1899.7	2797.3	2.4245	3.9318	6.3563
215	2105.9	0.001181	0.094680	918.02	1681.9	2599.9	920.50	1878.8	2799.3	2.4712	3.8489	6.3200
220	2319.6	0.001190	0.086094	940.79	1660.5	2601.3	943.55	1857.4	2801.0	2.5176	3.7664	6.2840
225	2549.7	0.001199	0.078405	963.70	1638.6	2602.3	966.76	1835.4	2802.2	2.5639	3.6844	6.2483
230	2797.1	0.001209	0.071505	986.76	1616.1	2602.9	990.14	1812.8	2802.9	2.6100	3.6028	6.2128
235	3062.6	0.001219	0.065300	1010.0	1593.2	2603.2	1013.7	1789.5	2803.2	2.6560	3.5216	6.1775
240	3347.0	0.001229	0.059707	1033.4	1569.8	2603.1	1037.5	1765.5	2803.0	2.7018	3.4405	6.1424
245	3651.2	0.001240	0.054656	1056.9	1545.7	2602.7	1061.5	1740.8	2802.2	2.7476	3.3596	6.1072
250	3976.2	0.001252	0.050085	1080.7	1521.1	2601.8	1085.7	1715.3	2801.0	2.7933	3.2788	6.0721
255	4322.9	0.001263	0.045941	1104.7	1495.8	2600.5	1110.1	1689.0	2799.1	2.8390	3.1979	6.0369
260	4692.3	0.001276	0.042175	1128.8	1469.9	2598.7	1134.8	1661.8	2796.6	2.8847	3.1169	6.0017
265	5085.3	0.001289	0.038748	1153.3	1443.2	2596.5	1159.8	1633.7	2793.5	2.9304	3.0358	5.9662
270	5503.0	0.001303	0.035622	1177.9	1415.7	2593.7	1185.1	1604.6	2789.7	2.9762	2.9542	5.9305
275	5946.4	0.001317	0.032767	1202.9	1387.4	2590.3	1210.7	1574.5	2785.2	3.0221	2.8723	5.8944
280	6416.6	0.001333	0.030153	1228.2	1358.2	2586.4	1236.7	1543.2	2779.9	3.0681	2.7898	5.8579
285	6914.6	0.001349	0.027756	1253.7	1328.1	2581.8	1263.1	1510.7	2773.7	3.1144	2.7066	5.8210
290	7441.8	0.001366	0.025554	1279.7	1296.9	2576.5	1289.8	1476.9	2766.7	3.1608	2.6225	5.7834
295	7999.0	0.001384	0.023528	1306.0	1264.5	2570.5	1317.1	1441.6	2758.7	3.2076	2.5374	5.7450
300	8587.9	0.001404	0.021659	1332.7	1230.9	2563.6	1344.8	1404.8	2749.6	3.2548	2.4511	5.7059
305	9209.4	0.001425	0.019932	1360.0	1195.9	2555.8	1373.1	1366.3	2739.4	3.3024	2.3633	5.6657
310	9865.0	0.001447	0.018333	1387.7	1159.3	2547.1	1402.0	1325.9	2727.9	3.3506	2.2737	5.6243
315	10,556	0.001472	0.016849	1416.1	1121.1	2537.2	1431.6	1283.4	2715.0	3.3994	2.1821	5.5816
320	11,284	0.001499	0.015470	1445.1	1080.9	2526.0	1462.0	1238.5	2700.6	3.4491	2.0881	5.5372
325	12,051	0.001528	0.014183	1475.0	1038.5	2513.4	1493.4	1191.0	2684.3	3.4998	1.9911	5.4908
330	12,858	0.001560	0.012979	1505.7	993.5	2499.2	1525.8	1140.3	2666.0	3.5516	1.8906	5.4422
335	13,707	0.001597	0.011848	1537.5	945.5	2483.0	1559.4	1086.0	2645.4	3.6050	1.7857	5.3907
340	14,601	0.001638	0.010783	1570.7	893.8	2464.5	1594.6	1027.4	2622.0	3.6602	1.6756	5.3358
345	15,541	0.001685	0.009772	1605.5	837.7	2443.2	1631.7	963.4	2595.1	3.7179	1.5585	5.2765
350	16,529	0.001741	0.008806	1642.4	775.9	2418.3	1671.2	892.7	2563.9	3.7788	1.4326	5.2114
355	17,570	0.001808	0.007872	1682.2	706.4	2388.6	1714.0	812.9	2526.9	3.8442	1.2942	5.1384
360	18,666	0.001895	0.006950	1726.2	625.7	2351.9	1761.5	720.1	2481.6	3.9165	1.1373	5.0537
365	19,822	0.002015	0.006009	1777.2	526.4	2303.6	1817.2	605.5	2422.7	4.0004	0.9489	4.9493
370	21,044	0.002217	0.004953	1844.5	385.6	2230.1	1891.2	443.1	2334.3	4.1119	0.6890	4.8009
373.95	22,064	0.003106	0.003106	2015.7	0	2015.7	2084.3	0	2084.3	4.4070	0	4.4070

Source of Data: Tables A–4 through A–8 are generated using the Engineering